NUMERICAL ANALYSIS OF THE EFFECTS OF SUSTAINED LOAD ON PIN-ENDED REINFORCED CONCRETE COLUMNS

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BY

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DECLARATION

I hereby declare that this thesis entitled "**Numerical Analysis of the Effects of Sustained Load on Pin-ended Reinforced Concrete Columns**" was prepared by me, with the guidance of my advisor. The work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted, in whole or in part, for any other degree or professional qualification.

Galata Kabeba Fole	___________	___________
Author	Signature	Date

CERTIFICATE

This is to certify that the thesis prepared by **Mr. Galata Kabeba Fole** entitled "**Numerical Analysis of the Effects of Sustained Load on Pin-ended Reinforced Concrete Columns**" and submitted as a partial fulfillment for the Degree of Master of Science complies with the regulations of the University and meets the accepted standards with respect to originality, content, and quality.

Date of defense: February 25, 2019

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ERA PG, Program Coordinator	Signature	Date
Department Head of Civil Engineering	Signature	Date
College Dean of Architecture and Civil Engineering	Signature	Date

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ABSTRACT

The reinforced concrete column is mainly subjected to compressive sustained axial load. The effect of the time-dependent concrete creep due to sustained axial load on the response of reinforced concrete column is not clearly known. To investigate this even though performing the experiment is necessary for accuracy, using ABAQUS 6.14-1, studying the time-dependent response of pin-ended reinforced concrete column is important to simplify certain difficulties that might be happening in keeping constant sustained axial load rate during an experimental study and to save time and cost.

A total of 90 pin-ended reinforced concrete columns of different cases are modeled. The study concerned with the numerical analysis of the time-dependent response of pin-ended reinforced concrete columns under concentrically applied sustained axial load. The nonlinear stress-strain relationships of concrete under sustained axial loading are developed by extending the nonlinear stress-strain relationships for short-term loading by multiplying all strain values by one plus creep coefficient to make the effect long-term. The considered time-dependent property of concrete is the compressive creep. The effect of sustained axial loading duration and magnitude are accounted through creep coefficient calculation.

The results obtained for the ultimate strength of the reinforced concrete column from ABAQUS 6.14-1 are compared with the analytical calculation according to the recommendation given in ACI-318-14 code and recommendation of Westerberg (2008) for validation and very good accuracy was obtained. Therefore, the material models and analysis used can simulate and represent the effects of concentrically applied sustained axial load on pin-ended reinforced concrete columns.

From the performed finite element simulation results, the concrete creep due to sustained axial loading does not significantly affect the ultimate strength of a pin-ended reinforced concrete column. It reduced the compressive stress in concrete obtained under short-term loading by about 85% and increased on reinforcing steel through time. The effects of parameters concrete grade, reinforcement ratio and length of the column on the time-dependent creep of concrete are also studied. From the parametric study, concrete grade and reinforcement ratio have a significant effect on concrete creep.

Key Words: ABAQUS, Creep, Sustained loading, Time-dependent analysis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A_c	The cross-sectional area of the concrete column
A_s	Cross-section area of reinforcement
ACI	American Concrete Institute
C-25	Concrete which has 25 MPa characteristic compressive strength
C-30	Concrete which has 30 MPa characteristic compressive strength
C-40	Concrete which has 40 MPa characteristic compressive strength
$E_{c,eff}$	Effective modulus of elasticity of concrete
E_{cm}	Secant modulus of elasticity of concrete
Es En-2	Ethiopian Standards based on Euro Norms
G_F	Fracture energy
K	The multiaxial behavior of the material model
K_σ	Stress-strength ratio
RH	Relative humidity of the ambient environment in %
S_{33}	The maximum compressive principal stress in concrete
S-400	Steel which has the yield stress of 400 MPa
c_1	Material constant
c_2	Material constant
d	Damage factor
d_c	Concrete compression damage
d_t	Concrete tension damage
f	Tensile or compressive strength of concrete
$\frac{f_{bo}}{f_{co}}$	Ratio of the strength in the biaxial state to the strength in the uniaxial state
f_c'	Concrete compressive strength
f_{ck}	Characteristic compressive strength of concrete
f_{cm}	Mean value of concrete cylinder compressive strength
f_{ctm}	Tensile strength of concrete
f(w)	Displacement function
f_y	Yield strength of reinforcing steel
f_{yk}	Characteristic yield strength of steel
h_o	Notional size of the member
P_u	The nominal ultimate strength of the reinforced concrete column

t	Age of concrete in days at the moment considered
t_o	Age of concrete at a loading
u	Perimeter of the member in contact with the atmosphere
w	Crack opening displacement
w_c	Crack opening displacement at which stress can no longer be transferred
$\alpha_{1/2/3}$	Coefficients to consider the influence of the concrete strength
$\beta_c(t, t_o)$	Coefficient to describe the development of creep with time after loading
$\beta(f_{cm})$	The factor to allow for the effect of concrete strength
$\beta(t_o)$	Factor to allow for the effect of concrete age at loading
β_H	Coefficient depending on relative humidity and the notional member size
ε_c	The total strain of concrete
ε_{c1}	Strain at peak stress
$\varepsilon_c{}^{el}$	The elastic strain of concrete
$\varepsilon_c{}^{in}$	Compressive inelastic strain of concrete
ε_c^{pl}	Concrete plastic strain
$\varepsilon_{cc}(t, t_o)$	Creep deformation of concrete
$\varepsilon_{ci}(t_o)$	Instantaneous strain of concrete
$\varepsilon_{cu\,1}$	Nominal ultimate strain
ν	Poisson's ratio
ρ	Reinforcement ratio for longitudinal reinforcement
σ_c	Compressive stress in the concrete
$\sigma_{c,Max}$	Maximum value of compressive principal stresses in concrete
σ_s	Von Mises stress of the reinforcement at maximum stress in concrete
$\varphi(t, t_o)$	Creep coefficient at time t
$\varphi_{nl}(t, t_o)$	Non-linear notional creep coefficient at time t
φ_o	Notional creep coefficient
φ_{RH}	Factor to allow for the effect of relative humidity

1. INTRODUCTION

1.1 Background

Reinforced concrete columns having different cross-sectional shape are widely used in construction industries. It is the structural members that carry loads mainly in compression and designed to transfer loads from superstructures to the soil through the foundations.

The sustained axial load is the load which constantly stays on the structure for the continuous period of time. The sustained axial load can cause the time-dependent deformation which can affect the structural response of the reinforced concrete columns. Thus, it is important to study its time-dependent response and the effect of different parameters. Studying the time-dependent response of reinforced concrete column under concentrically applied sustained axial load for different cases of concrete grades, column length and reinforcement ratio is important for getting knowledge that helps in designing it confidently.

Non-linear time-dependent analysis for the reinforced concrete column under sustained axial load is a difficult task. Experimental analysis can be carried out to study its response. This method predicts and provides the correct time-dependent response of the reinforced concrete column. But, a certain difficulty may happen in keeping constant sustained load rate during a test and also, it is costly and time taking study. In recent day's numerical analysis through finite element analysis software ABAQUS are attracting research area due to it is faster, modern computing techniques, easier and cost-effective than experimental study to perform the intended target. Therefore, in this research, the time-dependent finite element simulations of the pin-ended reinforced concrete columns are performed under concentrically applied sustained axial load through ABAQUS 6.14-1.

Finite element analysis is a method used for providing and predicting the response of different structures under different structural loads through meshing and assembling elements used for analysis.

The state of stresses due to sustained load promotes strains in concrete members which progresses over time, characterizing the phenomenon known as creep. In reinforced concrete columns, such deformations cause the stress increase in the steel bars of the reinforcement and may induce the material to undergo the yielding phenomenon (Madureira et al., 2013).

The time-dependent behaviors of concrete members that are of interest to the structural engineer are the shrinkage and the creep under sustained loads. Creep is defined as the time-dependent increase of strain in hardened concrete subjected to sustained stress. Shrinkage is defined as the decrease in concrete volume with time after hardening of concrete, which occur without stress attributable to actions external to the concrete (ACI 209, 2008).

The time-dependent property of concrete considered due to sustained axial loading is the creep of concrete. For short-term uniaxial loading, nonlinear stress-strain relationships for modeling concrete materials are developed according to equations of Es En-2 to carry out nonlinear finite element analysis. Under sustained axial loading, the effect of time-dependent concrete creep is accounted and predicted by modifying the model of a short-term loading. The modification consists of expressing all strain related to the compressive stress for concrete in terms of a function of time through creep coefficient calculation and given as input in ABAQUS. This is obtained according to the recommendation of Es En-2 which says the nonlinearity of concrete creep can be accounted by multiplying all strain values in the nonlinear stress-strain relationships by one plus creep coefficient.

1.2 Statement of the Problem

In structural engineering, the reinforced concrete column is mainly subjected to compressive sustained axial loading. The effect of time-dependent concrete creep due to sustained axial loading on the response of reinforced concrete column is not clearly known. To investigate this even though performing experiment is necessary for accuracy, the issue of the sustained axial load is challenging to perform experiments. Therefore, using finite element analysis software ABAQUS 6.14-1, it is intended to study the time-dependent effect of concrete creep on the response of the reinforced concrete column. Modeling time-dependent concrete creep in ABAQUS is also a problem because no easy method to account and investigate the non-linearity of concrete creep. In this research, nonlinear concrete creep is accounted according to Es En-2 recommendation and its possibility is suggested.

1.3 Objective of the Study

1.3.1 General Objective

The aim of this thesis is to study the time-dependent response of pin-ended reinforced concrete column under concentrically applied sustained axial load using ABAQUS 6.14-1.

1.3.2 Specific Objectives

- To study the effect of concrete creep.
- To study the effect of parameter reinforcement ratio.
- To study the effect of parameter concrete grade.
- To study the effect of parameter column length.

1.4 Scope of the Study

This research was limited to the time-dependent finite element analysis through ABAQUS 6.14-1 of pin-ended square reinforced concrete tie columns under concentric sustained axial load without lateral loads between their ends. The considered time-dependent effect in concrete is the compressive concrete creep. The geometric material nonlinearity and the buckling behavior of pin-ended reinforced concrete columns are not covered.

1.5 Significance of the Study

This research may be an input for further study and provides the time-dependent response of pin-ended reinforced concrete columns under concentrically applied sustained axial load. The possibility and accuracy of accounting concrete creep according to Es En-2 recommendation in concrete damaged plasticity model of concrete material through ABAQUS is presented. The effect of concrete creep in distributing the compressive stress from concrete to reinforcing steel and percentage of reduction of compressive stress in concrete and percent of increase on reinforcing steel through time is described. This thesis also presented the simulations and the distributions of concrete compressive and tensile damage, concrete strains and displacements with time over the part of reinforced concrete columns.

2. LITERATURE REVIEW

2.1 Introduction

Reinforced concrete columns are the structural member that is mainly subjected to sustained axial compressive load and designed to transfer loads safely. Hence, it is important to study the time-dependent response and strength of pin-ended reinforced concrete columns under sustained axial load. This is performed using finite element analysis software ABAQUS which saves time and cost.

2.2 Effect of Sustained Loading

There are a number of studies carried out on the effects of sustained load on the reinforced concrete structure. Also, a number of studies investigated the creep effects in reinforced concrete columns.

Concrete under stress undergoes a gradual increase of strain with time because of creep deformations of concrete. Generally, creep has little effect on the strength of a structure but it causes a redistribution of stress in reinforced concrete members at the service loads and leads to an increase in the service load deflections. The creep of concrete with sustained load results in a decrease in the concrete compressive stress and a considerable increase in the steel compressive stress. The increase in steel stress may even be sufficient to cause the steel to reach the yield strength at the service load. Concrete creep results in a shortening of the compressed part of the concrete cross section. Compression reinforcement reduces the influence of concrete creep because as the concrete compressive strains increase with time, some compressive stress is transferred gradually to the steel, resulting in reduced concrete compressive stress and reduced creep strains (Park and Paulay, 1975).

Creep is the time-dependent strain that develops in concrete due to sustained stress. Creep can dramatically change the stress distribution on a reinforced concrete section. Creep causes a redistribution of stresses between concrete and the bonded reinforcement on a cross-section. For a reinforced concrete column subjected to a constant sustained axial compressive load, as the compressive concrete creeps (contracts) the steel is compressed and the compressive stress in the steel gradually increases. Creep does not normally affect the strength of a structural member because the magnitude of creep strain is usually small compared to the peak strains at the ultimate load condition. However, creep affects structural behavior at service loads (Gilbert and Ranzi, 2011).

Columns in structures are subjected to sustained dead loads and sometimes to sustained live loads. The creep of the concrete under sustained loads increases the column deflections, increasing the moment and thus, causes a reduction in the failure load. The other column behavior under sustained load is creep buckling. The column deflections continue to increase under the sustained load, causing failure under the sustained load itself. This occurs only under high sustained loads greater than about 70% of the short-time capacity (Wight and Macgregor, 2012).

Simbirkin and Balevičius (2004) presented a method of non-linear analysis of load-carrying capacity and deformations of reinforced concrete columns subjected to long-term loads. They concluded that the non-linear response of reinforced concrete columns subjected to long-term loads can be modeled on the basis of the concrete creep and fracture theories using concrete stress-strain relations modified for long-term effects. The method proposed in their paper enables to take into account second-order geometrical effects.

Westerberg (2008) performed research on the time-dependent effects in the analysis and design of slender concrete compression members. He investigated a method of using an extended stress-strain curve for material models given in Eurocode 2, which states that the effect of concrete creep is taken into account by multiplying all strain values of the stress-strain diagram by a factor $(1 + \varphi(t, t_o))$. After comparison with test results, he concluded that the material models given in Eurocode 2 are realistic and there is no need for reduction of concrete strength with particular regard to high sustained stresses. According to his study with the normal conversion factor 0.85 included, the calculated results are generally conservative. However, he justified that the best overall agreement with test results is obtained without even this reduction and the concrete strength reduced by the conversion factor 0.85 can account for non-linearity of creep effect with better overall agreement.

Analysis of the load-bearing capacity of pin-ended hybrid headed columns under uniaxial loading using finite element simulations was conducted by Abdulhaq et al. (2011). According to their study, the ultimate load-bearing capacity of column decreases by increasing the length due to the increase in column slenderness and the effect of the column head on the ultimate load of the column is very significant. Also, they presented that load condition has a significant influence on the behavior and strength of the composite columns.

Sassone and Casalegno (2012) presented a method for the analysis of structural effects of time-dependent behavior of concrete, with particular regard to creep, based on the coupling of the finite element method. Their time-dependent analysis evidences the importance of taking into account the effects of time-dependent deformations of concrete in the design of tall buildings, in order to avoid long-term serviceability and safety concerns due to shortening of vertical members, and redistributions of internal actions.

The evaluation of the structural response to the time-dependent behavior of concrete was studied by Chiorino and Casalegno (2012). They concluded that modern concrete structures, realized through complex sequential construction techniques and characterized by significant non-homogeneities, are in general very sensitive to the effects of the delayed deformations of concrete.

Madureira et al. (2013) have presented the simulation of the creep strains on reinforced concrete columns. According to their results, concrete deformations cause the transfer of stresses from the concrete mass to the reinforcement steel bars which in turn have the effect of restraining creep strains, in some cases which induce the material to undergo the yielding phenomenon.

Through a comprehensive experimental program, geopolymer concrete columns subjected to axial load and biaxial bending was studied by Rahman (2013). He concluded that reinforcement ratio, the strength of concrete and load eccentricity influenced the load carrying capacity of the column significantly, and the load carrying capacity of test columns decreased when the load eccentricity increased and load capacity increased with the increase of concrete compressive strength and longitudinal reinforcement ratio.

McCormac and Brown (2014) described that under sustained compressive loads, concrete will continue to deform for long periods of time. According to his explanation, perhaps 75% of the total creep will occur during the first year. The amount of creep is largely dependent on the amount of stress. It is almost directly proportional to stress as long as the sustained stress is not greater than about one-half of f_c'. Beyond this level, creep will increase rapidly. Long-term loads not only cause creep but also can adversely affect the strength of the concrete. For loads maintained on concentrically loaded specimens for a year or longer, there may be a strength reduction of perhaps 15% to 25%.

An experimental study and numerical analysis of the time-dependent load transfer in the reinforced concrete columns were carried out by Kataoka and Bittencourt (2014). Their results indicated that numerical simulation does not predict the experimental data for a long period of time.

Gambali and Shanagam (2014) have researched on creep of concrete and presented that creep affects strain and often also stress distribution, but the effects vary with the type of structure. According to their study, the influence of creep on the ultimate strength of a simply supported reinforced concrete beam subjected to a sustained load is not significant, and in reinforced concrete columns, creep results in a gradual transfer of load from the concrete to the reinforcement. Also, they presented that the sustained stresses above the working stresses produce creep that increases progressively at a faster rate.

Lavanya and Tejaswi (2017) carried out an experimental study on creep characteristics of high strength concrete and concluded that the creep has an exponentially decreasing trend with time. The model they developed assists in predicting the time-dependent behavior of reinforced concrete columns in compression and uniaxial bending.

2.3 Non-linear Analysis through Finite Element Analysis Software ABAQUS

Dere and Koroglu (2017) have studied nonlinear finite element modeling of reinforced concrete through commercial ABAQUS software package along with the concrete damaged plasticity model. They suggested that compressive and tensile uniaxial stress-strain relationship as well as damage parameter curves for concrete material to be effectively used in ABAQUS. They verified the performance of their suggested constitutive and damage models with a simple nonlinear model and the analysis results were quite acceptable.

Chaudhari and Chakrabarti (2012) have presented modeling of concrete for nonlinear analysis through finite element analysis software ABAQUS using a case of smeared crack model and concrete damage plasticity approach. They concluded that in both cases the concrete shows a perfectly nonlinear behavior.

A material model for flexural crack simulation in reinforced concrete elements using ABAQUS was carried out by Wahalathantri et al. (2011). Their paper presented a material model which can be used to simulate the non-linear behavior of reinforced concrete elements and concluded that material model presented for reinforced concrete elements can simulate or assess the damage due to both tensile cracking and concrete crushing.

2.4 ES EN 1992-1-1:2015 Code Provisions on Material Properties

2.4.1 Elastic Behavior of Concrete

The behavior of concrete is elastic until it attains its yield strength. The modulus of elasticity can be calculated as:

$$E_{cm} = 22\left[\frac{f_{cm}}{10}\right]^{0.3} \quad \text{in (GPa)} \tag{2.1}$$

Where:

$$f_{cm} = f_{ck} + 8 \quad \text{in (MPa)} \tag{2.2}$$

2.4.2 Concrete Creep Effect

Creep is time-dependent properties of concrete. Its effect should generally be taken into account for the verification of serviceability limit states. Creep is influenced by the maturity of the concrete when the load is first applied and depends on the duration and magnitude of the loading. In the absence of more refined models, creep may be taken into account by multiplying all strain values in the concrete stress-strain diagram with a factor $(1 + \varphi(t, t_o))$.

When the compressive stress of concrete at age t_o exceeds the value $0.45f_{cm}(t_o)$ then creep non-linearity should be considered. In such cases the non-linear notional creep coefficient replaces $\varphi(t, t_o)$ and should be obtained as:

$$\varphi_{nl}(t, t_o) = \varphi(t, t_o)\exp(1.5(K_\sigma - 0.45)) \quad (2.3)$$

Where:

$$K_\sigma = \frac{\sigma_c}{f_{ck}(t_o)} \quad (2.4)$$

The basic equations for determining the creep coefficient $\varphi(t, t_o)$ that is time-dependent may be calculated from:

$$\varphi(t, t_o) = \varphi_o . \beta(t, t_o) \quad (2.5)$$

Where:

$$\varphi_o = \varphi_{RH} . \beta(f_{cm}) . \beta(t_o) \quad (2.6)$$

$$\varphi_{RH} = 1 + \frac{1 - \frac{RH}{100}}{0.1.\sqrt[3]{h_o}} \qquad \text{for } f_{cm} \leq 35 \text{ MPa} \quad (2.7a)$$

$$\varphi_{RH} = \left[1 + \frac{1 - \frac{RH}{100}}{0.1.\sqrt[3]{h_o}} . \alpha_1\right]\alpha_2 \qquad \text{for } f_{cm} > 35 \text{ MPa} \quad (2.7b)$$

$$\beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}} \quad (2.8)$$

$$\beta(t_o) = \frac{1}{0.1 + t_o^2} \quad (2.9)$$

$$h_o = \frac{2A_c}{u} \quad (2.10)$$

$$\beta_c(t, t_o) = \left[\frac{t - t_o}{\beta_H + t - t_o}\right]^{0.3} \quad (2.11)$$

$$\beta_H = 1.5[1 + (0.012RH)^{18}]h_o + 250 \leq 1500 \qquad \text{for } f_{cm} \leq 35 \text{ MPa} \quad (2.12a)$$

$$\beta_H = 1.5[1 + (0.012RH)^{18}]h_o + 250\alpha_3 \leq 1500\alpha_3 \qquad \text{for } f_{cm} > 35\ MPa \quad (2.12b)$$

$$\alpha_1 = \left[\frac{35}{f_{cm}}\right]^{0.7} \qquad \alpha_2 = \left[\frac{35}{f_{cm}}\right]^{0.2} \qquad \alpha_3 = \left[\frac{35}{f_{cm}}\right]^{0.5} \quad (2.12c)$$

The values of creep coefficient, $\varphi(t, t_o)$ calculated should be associated with a modulus of elasticity.

For loads with a duration causing creep, the total deformation including creep may be calculated by using an effective modulus of elasticity for concrete according to the expression:

$$E_{c,eff} = \frac{E_{cm}}{1+\varphi(t,t_o)} \tag{2.13}$$

2.4.3 Non-Linear Stress-Strain Relation of Concrete

The stress-strain relation of concrete for short-term uniaxial loading is developed by the expression:

$$\frac{\sigma_c}{f_{cm}} = \frac{k\eta-\eta^2}{1+(k-2)\eta} \tag{2.14}$$

Where:

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}}$$

$$\varepsilon_{c1} = \varepsilon_{c1}(‰) = 0.7{f_{cm}}^{0.31} \leq 2.8$$

$$k = 1.05E_{cm}\,x\,|\varepsilon_{c1}|/f_{cm}$$

The above expression is valid for $0 < |\varepsilon_c| < |\varepsilon_{cu1}|$.

The idealized stress-strain relation of concrete:

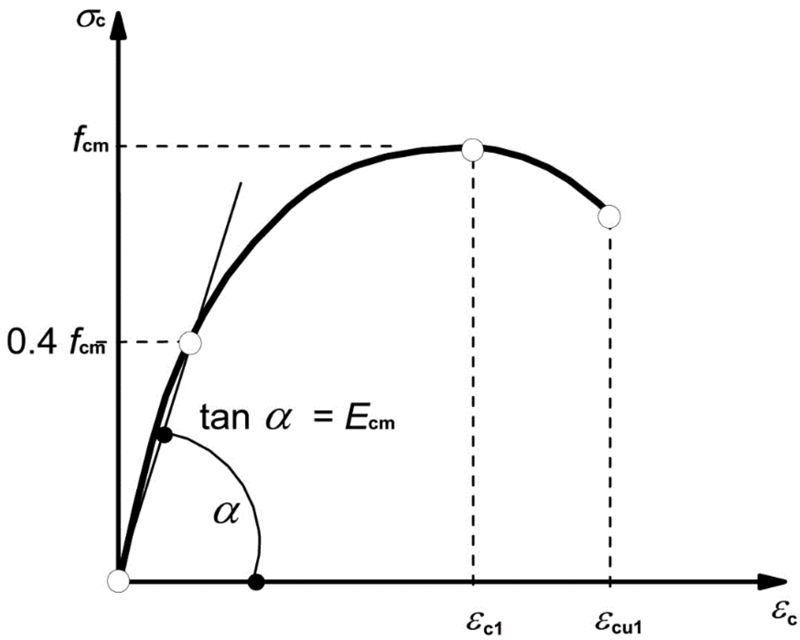

Figure 2.1: The stress-strain relation of concrete for structural analysis (Es En-2)

2.4.4 Reinforcing Steel

The behavior of reinforcing steel is specified based on Figure 2.2 and the application rules are valid for a specified yield strength range 400 to 600 MPa. The upper limit of f_{yk} within this range for use is found in Es En-2 National Annex C. Figure 2.2 shows the idealized and design stress-strain diagrams for reinforcing steel diagrammatically.

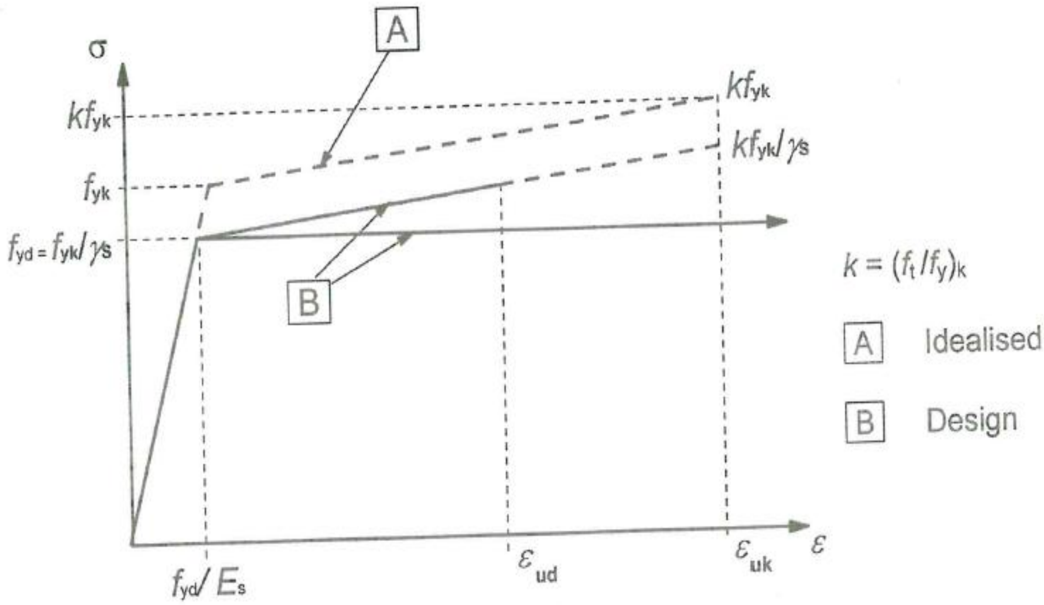

Figure 2.2: The stress-strain diagrams for reinforcing steel (Es En-2)

2.5 ACI Code Provision on Creep of Concrete

In reinforced concrete columns subject to sustained loads, creep transfers some of the load from the concrete to the longitudinal reinforcement, increasing the reinforcement stresses. Creep is separated into a basic creep and drying creep. Basic creep is the time-dependent increase in strain under a sustained constant load of a concrete specimen in which moisture losses or gains are prevented. It is considered a material constitutive property and independent of the specimen size and shape. Drying creep is the strain remaining after subtracting shrinkage, elastic and basic creep strains from the total measured strain on nominally identical specimens in a drying environment. The measured average creep of a cross-section at drying is strongly size-dependent (ACI 209, 2008).

3. METHODOLOGY

3.1 General

In Structural Engineering, the non-linear analysis of time-dependent effects in concrete is a very difficult task and requires a wide range of experimental works. Even though conducting experiments are necessary for the accuracy of research, performing many numbers of experiments are costly and time-consuming. Therefore, in this research finite element method is preferred with the use of ABAQUS 6.14-1 software. ABAQUS is a general purpose finite element program, intuitive software designed to model and carry out the intended task of structures under a certain applied load. A consistent unit should be used in ABAQUS since it does not have any built-in unit.

3.2 Description of the Reinforced Concrete Column Modeling

A total of 90 pin-ended square reinforced concrete tie columns are modeled for different cases. The reinforced concrete columns intended for the study has cross-sectional dimensions 350 mm both side. To carry out a parametric study, the concrete grade used is C-25, C-30 and C-40 and, three cases of continuous longitudinal reinforcement ratio 0.83%, 1.86% and 3.47% with 30 mm cover to reinforcement. The longitudinal reinforcement ratios are selected as it satisfies the criteria of Es En-2 minimum and maximum area of reinforcement. Lengths of the column used to carry out parametric study are 3000mm and 5500 mm. Stirrups are provided using 8 mm bar with 200 mm spacing.

The material model is assumed to be isotropic and homogeneous. To study the effect of concrete creep on the response of reinforced concrete columns, creep coefficient for different durations of loading should be determined. The magnitude of load affects the creep strain which influences the response of the column. Therefore, 3000 kN is used to represent the axial load on the reinforced concrete column.

The 500 mm x 500 mm analytical rigid plate is created to distribute the effect of concentrically applied sustained axial load uniformly over the top part of the column. The details for 3000 mm column in the case of minimum and maximum reinforcement ratio are shown in Figure 3.1.

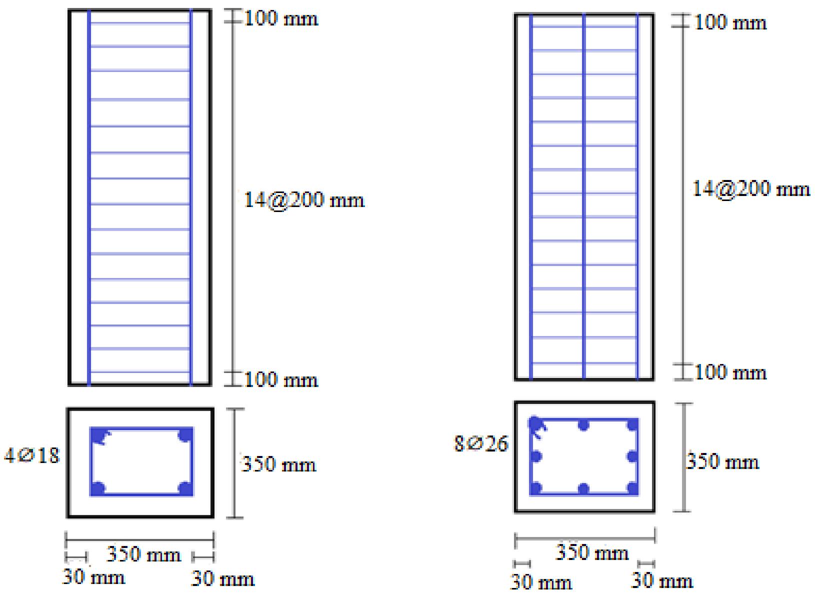

Figure 3.1: Outline of reinforced concrete tie column used for the study

In this research, three-dimensional finite element models are developed. The steps used for finite element modeling and performing the simulation of the time-dependent response of pin-ended reinforced concrete columns under concentrically applied sustained axial load using ABAQUS includes:

- Modeling geometry of parts
- Developing and assigning material properties
- Assembling parts and defining analysis steps
- Creating interaction between elements of parts
- Creating boundary conditions and applying a load or displacement
- Meshing
- Job assignment and visualization of results

3.3 Modeling Geometry

The three-dimensional parts that form the reinforced concrete column are created separately in ABAQUS/Standard software using create part option. These are:

- Concrete columns
- Reinforcing steel
- Stirrups
- Rigid plate

The three-dimensional parts created separately should be assembled together to form the complete model of the reinforced concrete column for analysis.

3.4 Model of Concrete Material

The two materials used in the model of reinforced concrete columns are concrete and steel. The column is made up of concrete. The two materials are combined to study the time-dependent response of pin-ended reinforced concrete column under concentrically applied sustained axial load. Concrete experiences an elastic and non-linear (plastic) behavior under compression load. As compression load is applied on concrete in the beginning, it shows elastic response and through time nonlinear response will occur. Finite element modeling should be capable of representing the elastic and plastic behavior of reinforced concrete in compression and tension.

3.4.1 Elasticity Behavior

The concrete shows linear elastic behavior in compression until it reaches its yield stress. To consider this the elastic behavior of concrete is defined by the linear elastic model in ABAQUS through elasticity option.

The Input data used to define elasticity is Young’s modulus and Poisson’s ratio. According to Es En-2, the density of normal weight concrete used is approximately 2400 kg/m^3 and Poisson’s ratio is 0.2 for uncracked concrete.

Table 3.1: Material properties of concrete for elastic behavior

Concrete properties	Concrete grade		
	C-25	C-30	C-40
f_{ck} (MPa)	25	30	40
$E_{cm}\,(MPa)$	31475.81	32836.57	35220.46
ν	0.2		
Density (kg/m^3)	2400		

3.4.2 Plasticity Behavior

3.4.2.1 Compressive Behavior for Short-term Loading

The concrete damaged plasticity model option is used to define the nonlinear properties of plain concrete outside the elastic range since it can describe the nonlinear behavior of concrete both in tension and compression including damage characteristics.

Development of a proper damage simulation model using the concrete damaged plasticity model will be useful for the analysis of reinforced concrete structures under any loading combinations including both static and dynamic loading (Abaqus user's manual, 6.14). This model is based on the assumption of scalar (isotropic) damage. In concrete damaged plasticity model, the two main failure mechanisms in concrete are the tensile cracking and the compressive crushing. The uniaxial tensile and compressive behavior is characterized by damaged plasticity. The selected material model can describe plasticity, compressive behavior, and tension stiffening effect.

The compressive behavior is defined by the yield stress (σ_c) as a function of inelastic strain (ε_c^{in}) and specified in ABAQUS as tabular data. The first row of the table is defined by the point where the concrete starts to exhibit a nonlinear behavior (inelastic straining). According to Malm (2006), the stress at this point can be estimated at 30% of the ultimate compressive strength. The inelastic strain at this point must be zero in ABAQUS.

The remaining non-linear stress-strain relationships of concrete are determined according to equation (2.14) where the numbers of points are selected to describe the compressive behavior depending on the desired accuracy. For the total strain of concrete, the points are tabulated up to the ultimate strain of concrete.

According to ABAQUS Analysis user's Manual 6.14, hardening data are given in terms of inelastic strain which is calculated as equation (3.1). The compressive inelastic strain (ε_c^{in}) is defined as total strain (ε_c) minus elastic strain (ε_c^{el}) corresponding to the undamaged material. Elastic strain (ε_c^{el}) is calculated as dividing yield stress in concrete (σ_c) by its modulus of elasticity (E_c).

$$\varepsilon_c^{in} = \varepsilon_c - \varepsilon_c^{el} \tag{3.1}$$

$$\varepsilon_c^{el} = \frac{\sigma_c}{E_c} \tag{3.2}$$

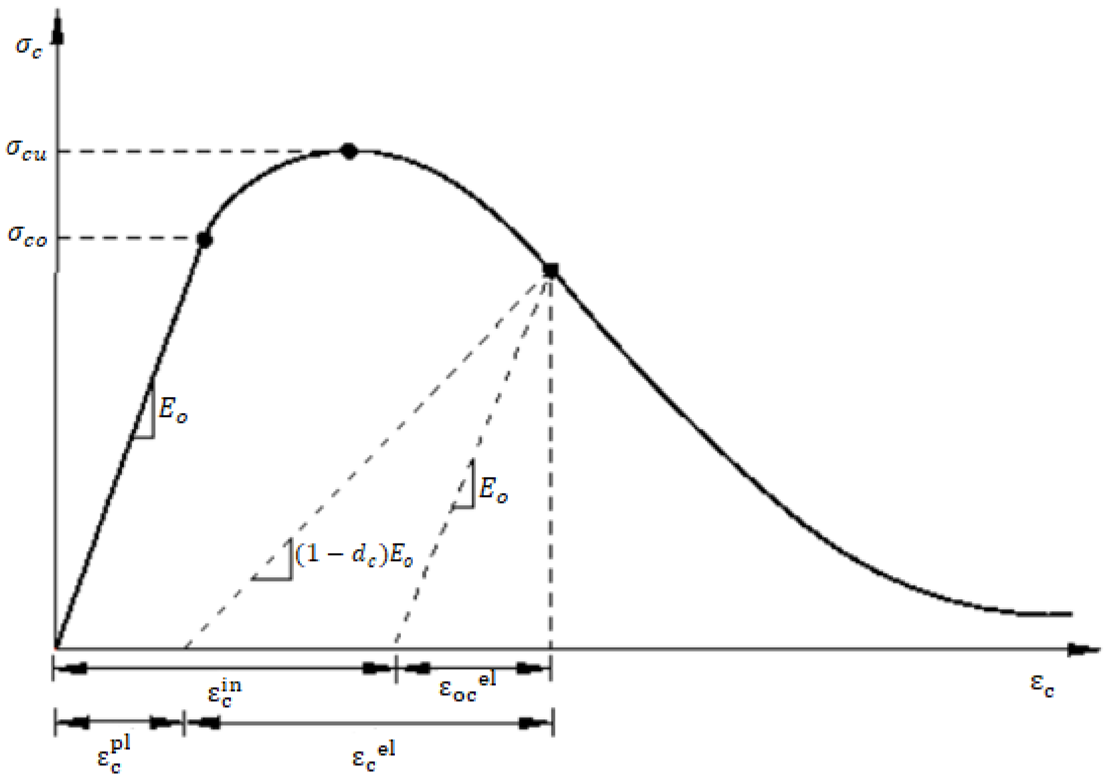

Figure 3.2: Response of concrete to uniaxial loading in compression (Abaqus user's manual, 6.14)

Figure 3.3 shows the developed non-linear stress-strain response of C-30 concrete to uniaxial compressive loading. The summary of the developed concrete materials model used for analysis is given in Appendix A.

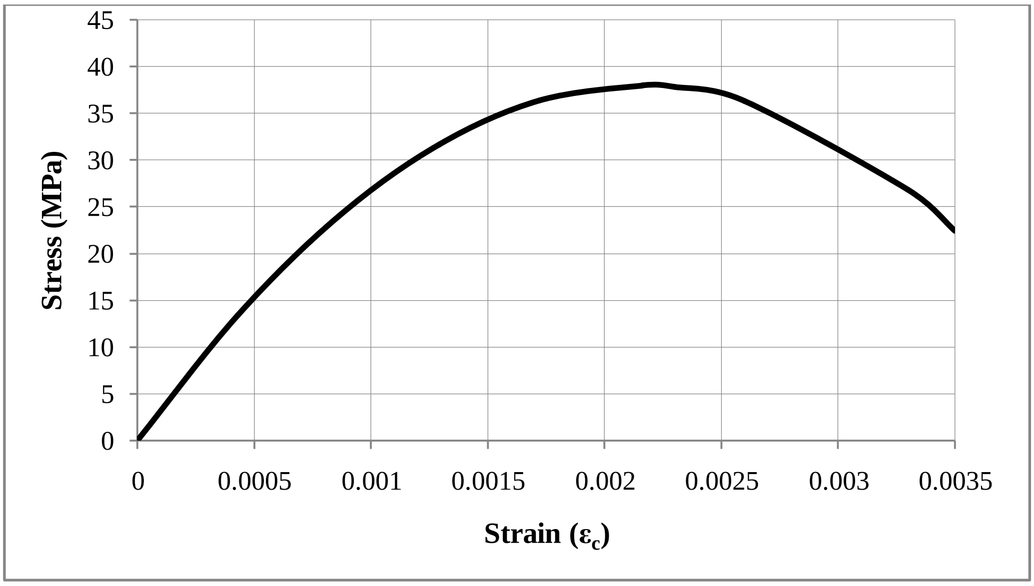

Figure 3.3: Stress-strain relationship developed for modeling C-30 concrete

Lubliner et al. (1989) proposed a simple damage model that plastic degradation occurs only in the softening range and under uniaxial tension or compression, damage factor d can be determined as:

$$d = 1 - \frac{\sigma}{f} \tag{3.3}$$

f is either the tensile or compressive strength of concrete as appropriate. Therefore,

$$d_c = 1 - \frac{\sigma_c}{f_{cm}} \tag{3.4}$$

If compression damage is specified, ABAQUS automatically converts the inelastic strain values to plastic strain values using the relationship:

$$\varepsilon_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1-d_c)} \frac{\sigma_c}{E_c} \tag{3.5}$$

ABAQUS shows an error message if the calculated plastic strain values are negative and/ or decreasing with increasing inelastic strain, which typically indicates that the compressive damage curves are incorrect.

3.4.2.2 Creep of Concrete due to Sustained Axial Loading

Sustained load causes creep of concrete. In this study, compressive concrete creep for the different duration of axial loading is considered through the compressive behavior of concrete damaged plasticity model. The compressive concrete creep is determined according to the recommendation of Es En-2 which states that creep can be taken into account by multiplying all strain values in the concrete nonlinear stress-strain diagram with a factor $(1 + \varphi(t, t_o))$. The inelastic strain calculated as equation (3.1) is multiplied by a factor $(1 + \varphi(t, t_o))$ and given as input in ABAQUS replacing inelastic strain (ε_c^{in}) of short-term loading for a different time.

Creep coefficient is a function of time and the magnitude of sustained axial loading. According to Es En-2, when the compressive stress of concrete at age t_o exceeds the value $0.45f_{cm}(t_o)$ then creep non-linearity should be considered. In this thesis, the sustained stress is 24.5 MPa (3000 kN) which is about 65% of C-30 concrete compressive strength (f_{cm}) and greater than $0.45f_{cm}(t_o)$, therefore creep non-linearity is considered. In such cases, the non-linear notional creep coefficient should be used and obtained as equation (2.3). Since creep of concrete affects the modulus of elasticity of concrete through time, effective modulus of elasticity is used for time-dependent analysis. Effective modulus of elasticity of concrete can be determined according to equation (2.13).

The age t_o of 28 days was chosen to simulate the condition of concrete of actual structures at the end of curing and removal of formwork on site to fully carry the load. To study the time-dependent effect in concrete on the response of reinforced concrete column, the sustained axial loading is considered for durations of 2, 5, 10 and 20 years. According to Ethiopia metrological agency, the average annual relative humidity of Addis Ababa 60.7% was taken to determine the creep coefficient.

Table 3.2: Calculated concrete creep coefficient

Time (t)	Creep Coefficient, $\varphi_{nl}(t, t_o)$		
	C-25	C-30	C-40
t_o=28 days	0	0	0
t=2 year (731 days)	3.199	2.481	1.629
t=5 year (1827 days)	3.498	2.709	1.773
t=10 year (3655 days)	3.624	2.805	1.834
t=20 year (7310 days)	3.695	2.859	1.867

Table 3.3: Effective modulus of elasticity of concrete

Concrete grade	C-25	C-30	C-40
E_{cm} at 28 days (MPa)	31475.81	32836.57	35220.46
Time (year)	Effective modulus of elasticity (MPa)		
t=2 year	7495.55	9433.89	13395.49
t=5 year	6998.28	8853.56	12699.08
t=10 year	6806.46	8628.94	12428.49
t=20 year	6704.19	8509.03	12283.89

According to Gilbert and Ranzi (2011), under normal conditions, the creep coefficient at time infinity under constant sustained stress is between 1.5 and 4. Since the calculated creep coefficient lies between 1.5 and 4 it was correctly determined. The calculated creep coefficients were summarized in Table 3.2 and graphically drawn as in Figure 3.4.

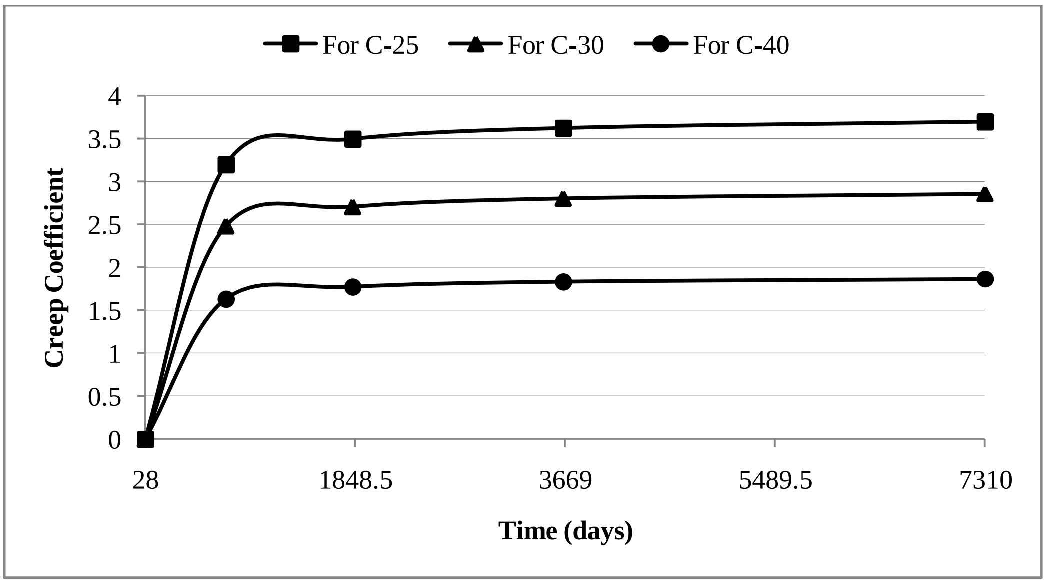

Figure 3.4: Variation of concrete creep coefficient with time

3.4.2.3 Tensile Behavior

The tensile behavior is defined by the yield stress as a function of displacement to account tension stiffening effect. When concrete cracks under sustained axial load, some amount of load is transferred to reinforcement across cracks and carried by it. This effect is known as tension stiffening effect and considered through tensile behavior sub-option of concrete damaged plasticity model.

The tension stiffening can either be defined as stress-strain or stress-displacement. It is recommended to use the stress-displacement alternative to avoid mesh sensitivity in regions that lack reinforcement. Another reason to use this approach is that the tensile behavior does not need to be redefined if the mesh is changed, which is the case for the stress-strain alternative (Malm, 2006). Therefore, in this thesis, the stress-displacement alternative is used.

According to ABAQUS Analysis user's Manual 6.14, the post-failure behavior for direct straining is modeled with tension stiffening, which allows defining the strain- softening behavior for cracked concrete. This behavior allows for the effects of the reinforcement interaction with concrete to be simulated in a simple manner. Tension stiffening is required in the concrete damaged plasticity model. Tension stiffening is specified by means of post-failure stress-displacement relation.

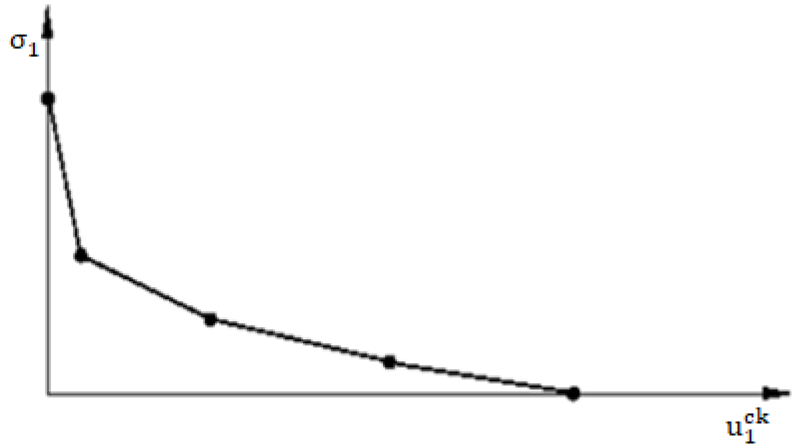

Figure 3.5: Stress-displacement for tension stiffening model (Abaqus user's manual, 6.14)

According to Karihaloo (2003), the by far best and most accurate model of the stress-displacement curve is the exponential function experimentally derived by Cornelissen et al. (1986). The following exponential model was proposed by Cornelissen et al. (1986).

$$\frac{\sigma}{f_{ctm}} = f(w) - \frac{w}{w_c} f(w_c) \tag{3.6}$$

Where: $f(w)$ is a displacement function given by

$$f(w) = [1 + \left(\frac{c_1 w}{w_c}\right)^3]\exp(-\frac{c_2 w}{w_c}) \tag{3.7}$$

Where: w is the crack opening displacement

w_c is the crack opening displacement at which stress can no longer be transferred

$w_c = 5.14 \frac{G_f}{f_{ctm}}$ for normal weight concrete

c_1 is a material constant and $c_1 = 3$ for normal density concrete

c_2 is a material constant and $c_2 = 6.93$ for normal density concrete

According to the CEB-FIP Model code 2010, G_F ($\frac{N}{mm}$) can be calculated as:

$$G_F = 0.073\, {f_{cm}}^{0.18} \tag{3.8}$$

Where: G_F is a fracture or crushing energy that describes the amount of energy that is needed to open a unit area of crack, to obtain stress-free crack.

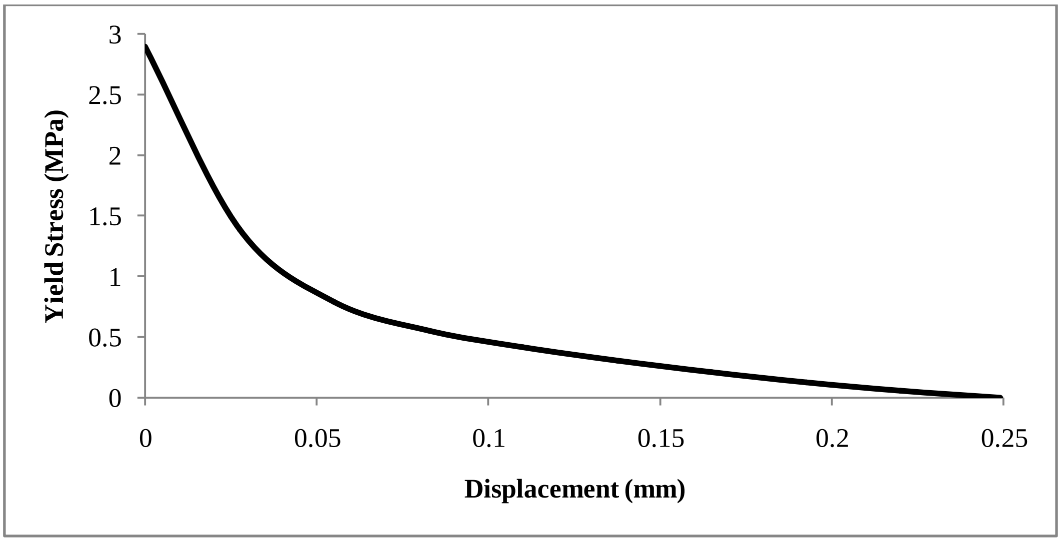

Figure 3.6: Developed exponential tension stiffening model for C-30

3.5 Model of Steel Material

Steel is used for modeling reinforcement and stirrup. In ABAQUS, reinforcing steel and stirrup are modeled using wire shape with truss elements for which the only input parameter required is the cross-sectional area of reinforcement and stirrup. Stirrups were included since reinforcing steel is modeled as wire. The steel material was defined as elastic-perfectly plastic material to include both elasticity and plasticity behavior of steel. The plastic properties of reinforcing steel and stirrup were assumed based on the bilinear steel curve of Es En-2 and assumed to have yielding stress of 400 MPa.

Table 3.4: Elastic-plastic material properties used for S-400 normal steel

Elastic Property			**Plastic Property**	
Modulus of Elasticity (MPa)	Density (Kg/m^3)	Poisson's Ratio	Yield Stress (MPa)	Plastic Strain
200000	7850	0.3	400	0
			540	0.075

3.6 Analysis Step

The assembled parts together to form the complete model of the reinforced concrete column are analyzed under sustained axial load. The step module in ABAQUS is used to define the intended analysis steps through creating step sub-option. In this study, the method used to perform the intended non-linear finite element analysis is the incremental direct equation solver method using full Newton solution technique. The analysis procedure is performed using Static Riks and Static General. Static Riks procedure is suitable for the prediction of the response of reinforced concrete column up to ultimate strength and after it, using the load-controlled method. Static General is used to performing the parametric study under a sustained axial load of magnitude 3000 kN. Geometric nonlinearity is not considered.

The incremental analysis size is fixed as sufficient solution accuracy is obtained. For Static Riks it is fixed initially from 0.1 and increases by a minimum of 1E-015 up to 1, which is maximum increment size. The incremental analysis procedure continues until the maximum number of increments is reached. For this study, the maximum number of incremental iterations is fixed to 50 because the ultimate response is obtained before that.

For Static General, the incremental analysis size is fixed initially from 0.1 and increases by a minimum of 1E-005 up to 1, which is the maximum increment size. The incremental analysis procedure continues until the solution converges. When solution converges before the maximum number of increment is reached, the ABAQUS says the analysis is completed if not it says aborted. In this research, the maximum number of increment is limited to 100 because the solution converges before that.

Table 3.5: Step defined for finite element analysis

Step no.	Name	Analysis procedure	Maximum no. of increments	Increment size		
				Initial	Minimum	Maximum
1	Initial					
2	Prediction of ultimate response	Static, Riks	50	0.1	1E-015	1
3	Analysis under load of 3000 kN	Static, General	100	0.1	1E-005	1

3.7 Interaction

The interaction between the created element parts are defined through create constraint sub-option from interaction module of ABAQUS. The created parts to form complete reinforced concrete column were a concrete column, reinforcing steel, stirrups and analytical rigid plate. The embedded element option was used for connecting the reinforcement and stirrup element to concrete column host element. The analytical rigid plate is attached to the column by the tie.

Table 3.6: Interaction types defined for the model

No.	Constraint name	Constraint type
1	Reinforcement and stirrup in concrete	Embedded region
2	Analytical rigid plate to the column	Tie
3	The point at loading to the analytical rigid plate	Rigid body

3.8 Boundary Condition and Load Application

The bottom end of the column is pinned in all directions. The top end of the column is pinned in X and Z direction allowing displacement in Y-direction. The pin-ended reinforced concrete columns were loaded with concentric 3000 kN sustained axial load in Y-direction and allowed to move freely in Y-direction but pinned in X and Z direction. The analytical rigid plate was created to distribute the applied compressive sustained axial load effect uniformly over the top part of the column.

Figure 3.7 shows the created boundary condition of reinforced concrete column and application of axial load in negative Y-direction.

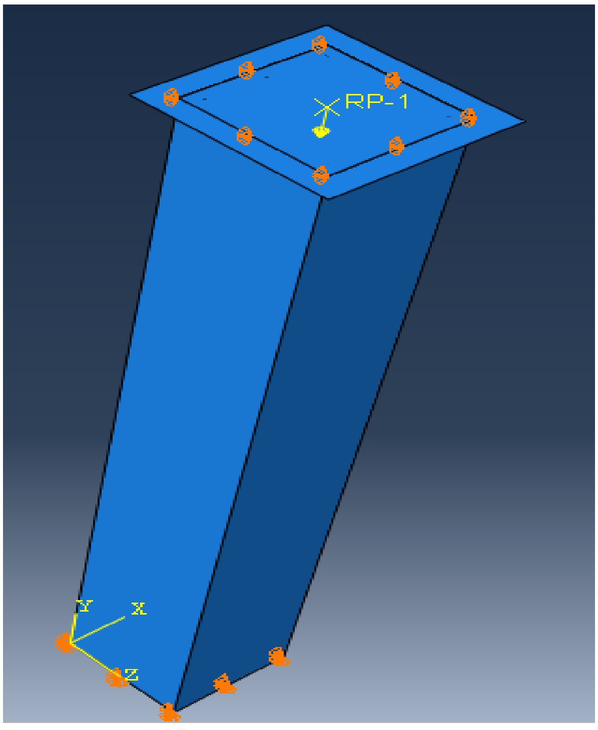

Figure 3.7: Boundary condition and application of load

3.9 Meshing

Mesh size affect the accuracy of the result in a method of finite element simulations. Mesh size is selected to give sufficient accuracy and not to make the runtime too long. In the finite element analysis, the region of the model is divided into small parts and the ABAQUS calculates a solution over each element. After conducting many trials runs using different finite element mesh size, a sufficient accuracy was obtained by 30 mm mesh size and it is used for this study. The concrete column was modeled using 8-node linear brick reduced integration, C3D8R. The reinforcing bars and stirrups were modeled using a 2-node linear 3-D truss elements T3D2. Table 3.7 shows element type and a number of elements used in modeling 3000 mm reinforced concrete column.

Table 3.7: Element type and number of elements used in modeling

Part	Element type	No.of elements	No. of nodes
Concrete column	Hex(C3D8R)	14400	17069
Rebars	Truss(T3D2)	100	101
Stirrups	Truss(T3D2)	116	116

Figure 3.8 shows the finite element mesh for 3000 mm reinforced concrete column.

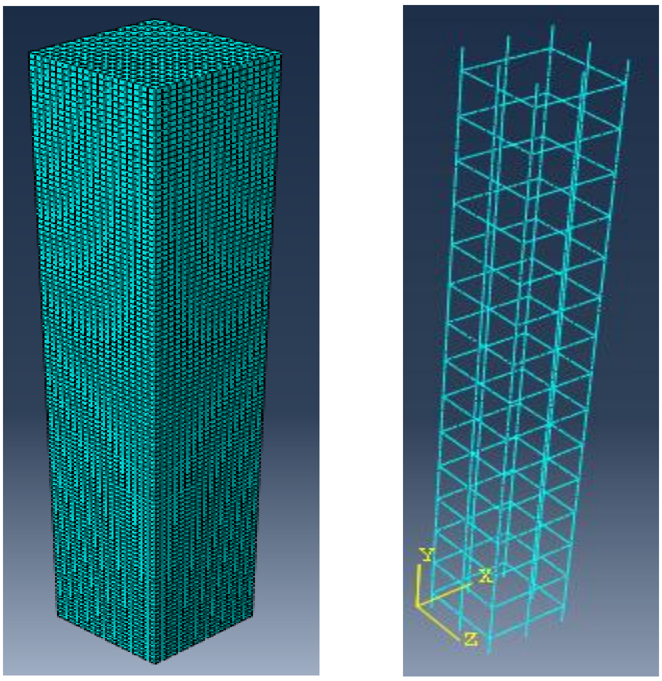

Figure 3.8: Meshing of concrete column and tied reinforcement bar

3.10 Results Monitored

In ABAQUS to perform the intended finite element analysis, the correct job should be defined. The job defined for this study along with the created steps is the static analysis through ABAQUS/Standard. Then, the job defined is submitted for the analysis. After the analysis is completed the intended results are monitored graphically with time domain for further discussions. The following results were monitored during the study of the time-dependent response of pin-ended reinforced concrete columns under sustained axial loading.

- Prediction of strength-displacement response
- Maximum compressive stress in concrete and reinforcing steel
- Maximum principal strain in concrete
- Concrete compression damage
- Concrete tension damage

4. FINITE ELEMENT MODEL VALIDATION

4.1 General

A numerical finite element analysis using ABAQUS is interesting only if it can represent the behavior of the real model. Therefore, to verify the accuracy of the finite element model comparison was done with the recommendation of ACI-318-14 code as the calculation of equation (4.1) and Westerberg (2008) recommendation.

4.2 Analytical Verification

The accuracy of the nonlinear stress-strain and stress-displacement relation used in modeling concrete materials were verified through the determination of the ultimate strength of the reinforced concrete column. Also, the elastic-plastic value taken for reinforcing steel was checked through the strength calculation in combination with concrete. Once a model is verified for the 3000 mm column of concrete grade C-25, C-30, and C-40, it can be extended for the simulation of different parametric cases.

The nominal ultimate strength of the reinforced concrete column as recommended by ACI 318-14 can be calculated as:

$$P_u = 0.85\, f_c'(A_c - A_s) + A_s f_y \tag{4.1}$$

Westerberg (2008) studied the time-dependent effects in the analysis and design of compression members and concluded that the best overall agreement of strength analysis with test results is obtained without the normal conversion factor 0.85 for concrete. In this research, the obtained results from ABAQUS 6.14-1 best agree with the conclusion of Westerberg (2008). From the comparison of calculated values with ABAQUS 6.14-1 results, very good accuracy is obtained with a difference of less than 2.5%. Therefore, the material models used for finite element analysis were correct. The recommendation given in ACI 318-14 code to determine the ultimate strength of reinforced concrete column underestimates the ultimate strength of the reinforced concrete column.

The comparisons are given in the following Figures.

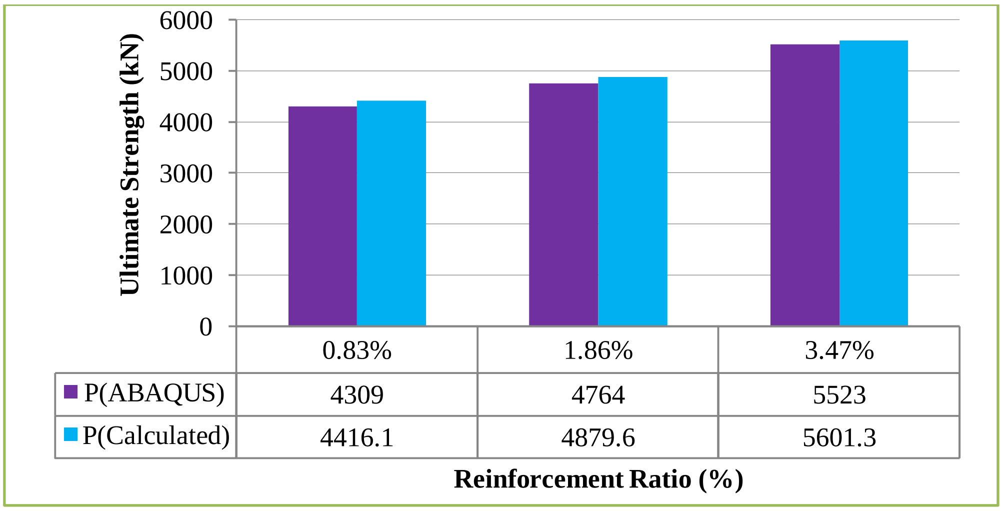

Figure 4.1: Model validation for C-25

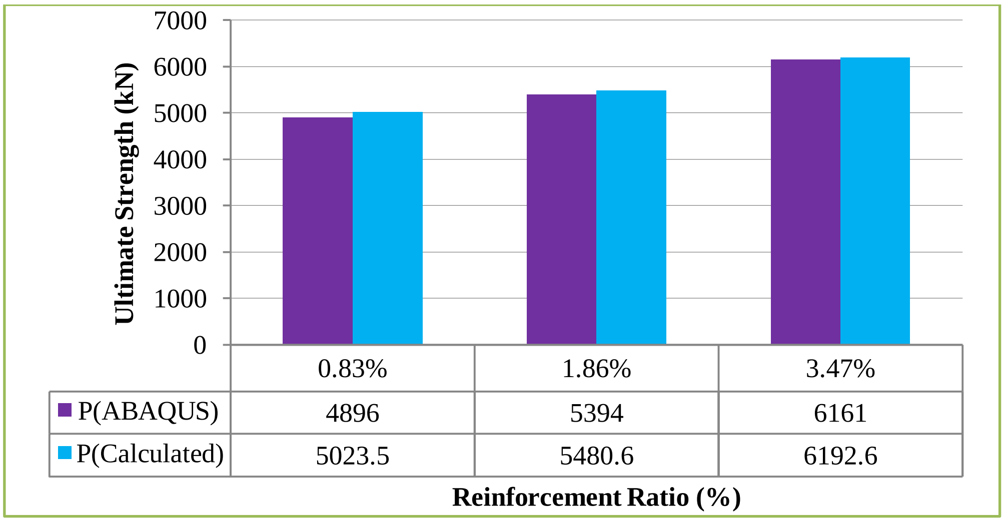

Figure 4.2: Model validation for C-30

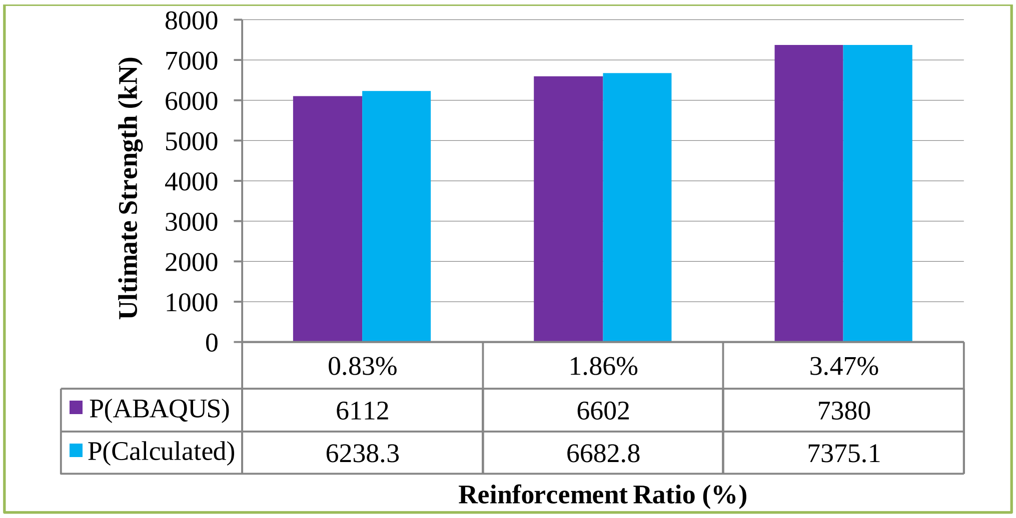

Figure 4.3: Model validation for C-40

5. RESULTS AND DISCUSSIONS

5.1 General

The results obtained from the finite element analysis are presented in this chapter. A concentrically applied sustained axial load was uniformly applied on the pin-ended reinforced concrete columns in order to study its effects with time through ABAQUS 6.14. From the finite element simulations, the results considered to depict the time-dependent response of reinforced concrete column were compressive stress in concrete and reinforcement, concrete strain, displacement and ultimate strength of reinforced concrete column. The parts of the concrete column damaged by compression and tension were also simulated. The considered durations of loading for the analysis under sustained axial loading are 2, 5, 10, and 20 years. These durations were accounted through creep coefficient calculations which are used to determine the time-dependent inelastic strain of concrete in concrete damaged plasticity model.

5.2 Time-Dependent Response of Reinforced Concrete Column

The finite element analysis was performed in order to simulate the time-dependent response of reinforced concrete column for different durations of sustained axial loading. The results summary of peak strength, the compressive stress in concrete and reinforcement obtained from ABAQUS for different parameters are summarized in Appendix C. The considered the time-dependent property of concrete was only creeping of concrete. Therefore, under sustained axial loading, a strain or displacement in excess of the value obtained for short-term loading analysis is due to the creep of concrete. The time-dependent increase or decrease of compressive stress in concrete and reinforcing steel for short-term analysis is due to accounted creep of concrete.

Due to a vast number of elements and nodes obtained for the mesh of finite element models, the plot of results with time is presented for the elements and nodes at which peak response of strength and compressive stress in concrete is obtained. For this section, the discussions are given for 3000 mm column length, C-30, and reinforcement ratio of 3.47% for different durations of loading. The others are intended for a parametric study on the time-dependent response.

5.2.1 Strength-Displacement Response

Figure 5.1 depicts the effects of concrete creep on the time-dependent response of the ultimate strength of the reinforced concrete column.

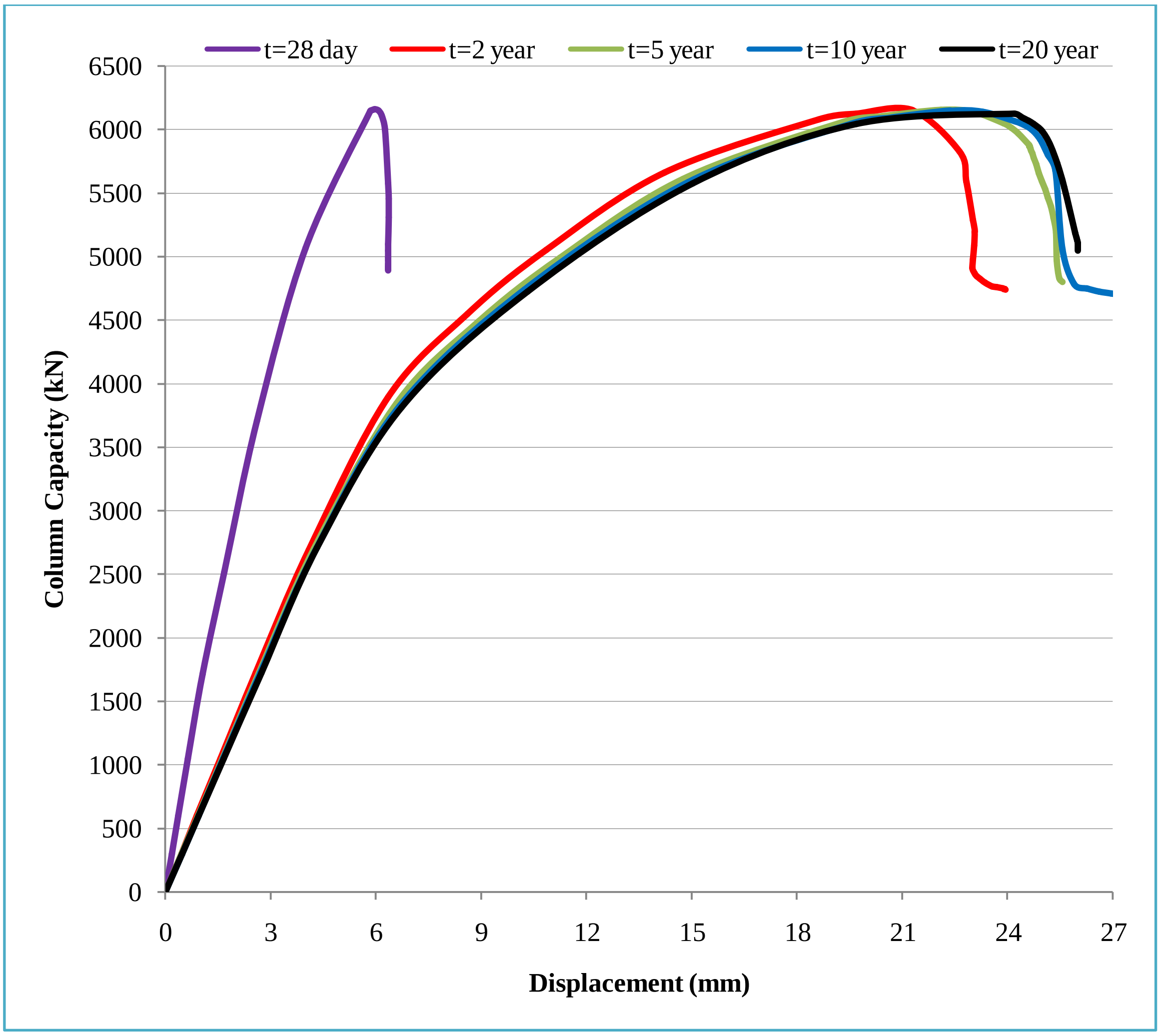

Figure 5.1: Strength-displacement response for the different time

As it can be seen from the graph, compressive creep of concrete does not affect the ultimate strength of the reinforced concrete column but it significantly increases the displacement of the concrete column with time. The increase in displacement with time increases the strain in concrete which makes concrete deforms continuously. As concrete cracks, the compressive load is shared on reinforcing steel and it supports concrete. Creep of concrete has no significant influence on the ultimate strength of reinforced concrete column but it distributes the compressive stress from concrete to reinforcing steel. This concept is presented in section 5.2.2.

The effect of concrete creep on the ultimate strength of reinforced concrete column and vertical displacement with time can be depicted from the simulation results used to draw Figure 5.1 by selecting the peak values of strength and displacement at which it obtained for the different time.

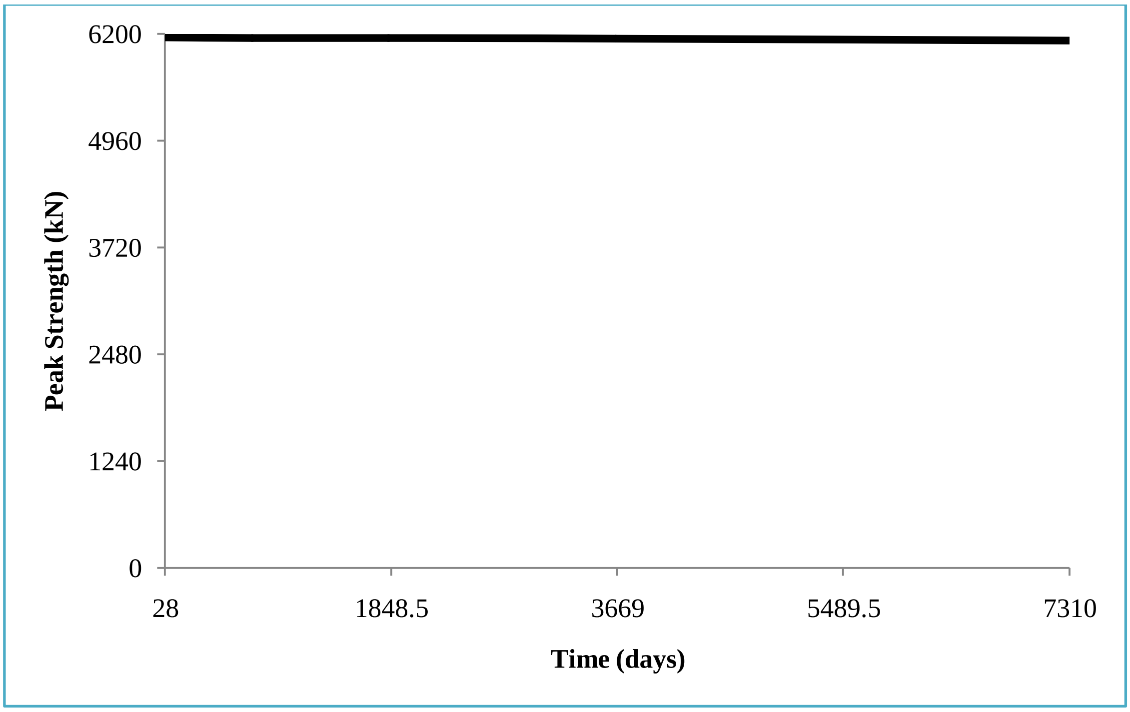

Figure 5.2: Ultimate strength of reinforced concrete column with time

The time-dependent vertical displacement of the concrete column due to sustained axial loading is shown in Figure 5.3.

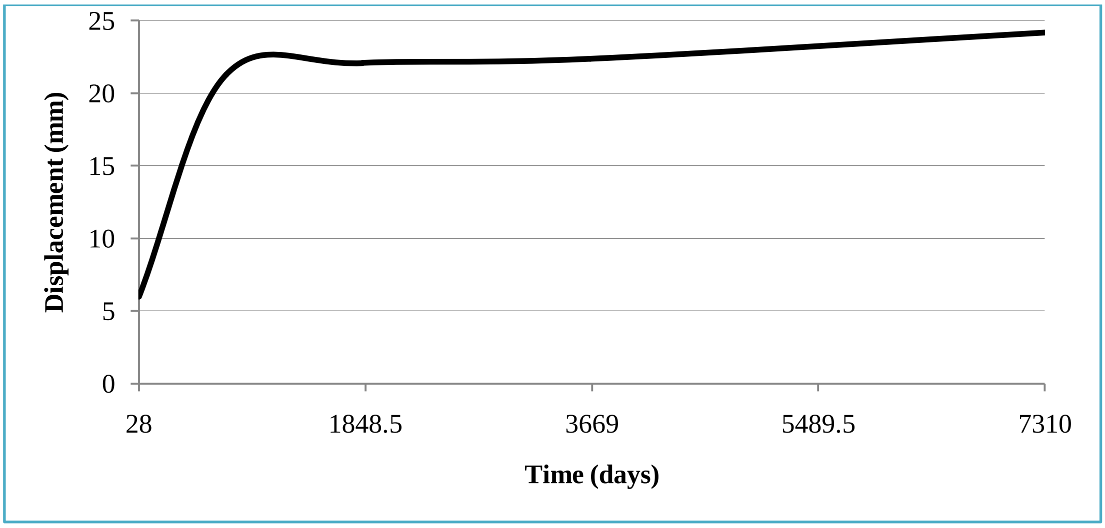

Figure 5.3: Vertical displacement of the column with time

In general, the results of performed finite element analysis indicate that creep of concrete does not reduce the load-carrying capacity of reinforced concrete columns. It increased the vertical displacement of columns through time. Displacement increased rapidly during the first 2 years and increases slowly after that. This was due to the calculated concrete creep strain increases rapidly during the first 2 years and increases slowly after 2 years as it can be seen from the calculated creep coefficient in Figure 3.4.

5.2.2 Compressive Stress in Concrete and Reinforcing Steel

The performed finite element analysis predicted the time-dependent response of compressive stress in concrete and reinforcing steel. The time-dependent reduction of compressive stress in concrete and the percentage by which the compressive stress in concrete under short-term loading is reduced due to the compressive creep of concrete are presented. From the visualization of results given by ABAQUS, the maximum compressive principal stress in concrete is obtained for S_{33} and it is used to depict the time-dependent compressive stress in concrete. For reinforcing steel, Von Mises stress is used to describe the time-dependent stress on reinforcing steel.

For the analysis under sustained axial loading of different durations, the contour visualization which shows the node and element at which peak compressive stress in concrete obtained is given in Appendix C. Figure 5.4 shows the node and element at which the peak principal stress in the concrete of the model under short-term loading analysis is obtained. It is selected among the different increments of the performed analysis done by ABAQUS.

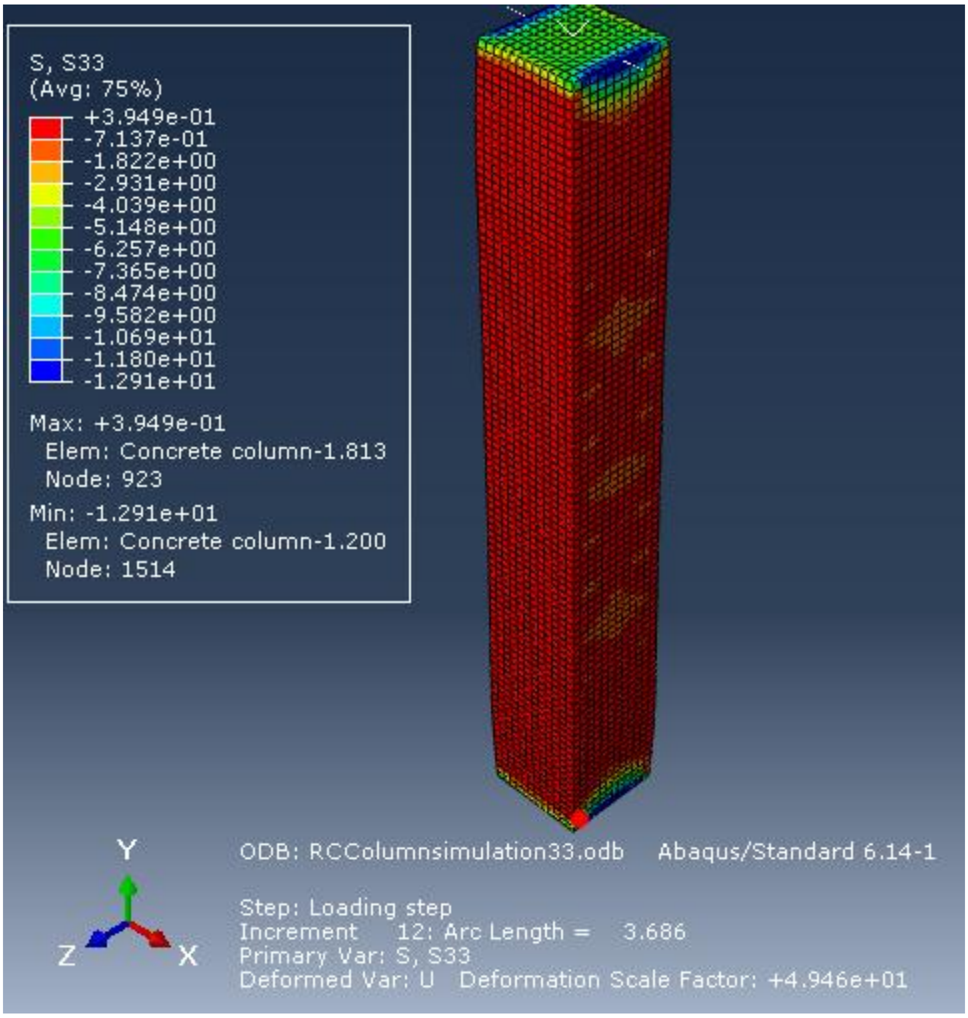

Figure 5.4: Peak principal stress in concrete column (t=28 days)

From Figure 5.4, it can be seen from the contours that the bottom and the top part of the reinforced concrete column experiences compressive stress in concrete (negative stress value in ABAQUS) while the part of the column along its height experiences tension in concrete (positive stress value in ABAQUS).

The time-dependent compressive stress in concrete for a model of different loading duration is depicted by selecting the peak magnitude of S_{33} from different simulation increments and for reinforcing steel the Von Mises stress value at the analysis increment of peak compressive stress in the concrete column is taken.

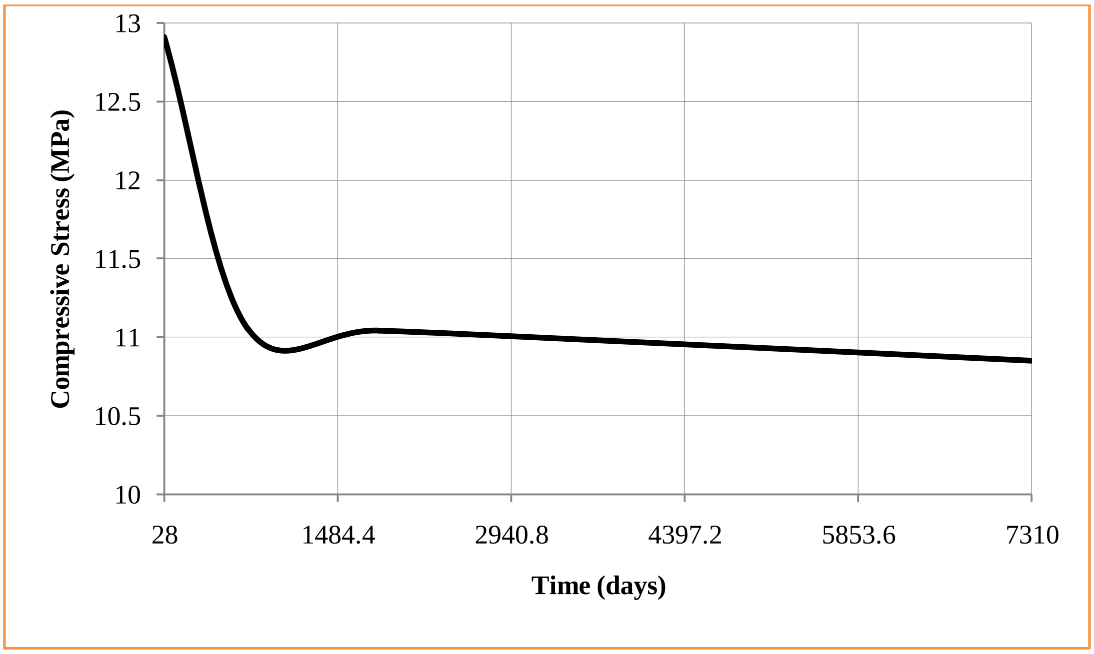

Figure 5.5: Time-dependent compressive stress in concrete

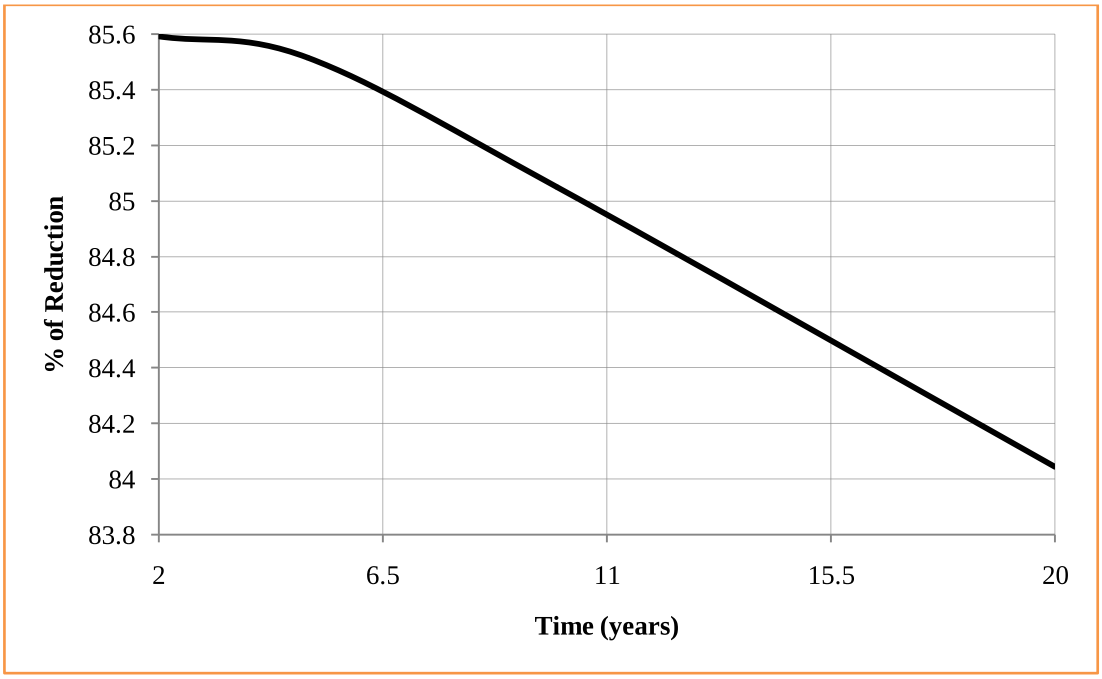

Figure 5.6: Percentage of reductions of compressive stress in concrete with time

From Figure 5.5, the high compressive stress in the concrete occurred at the time of loading. Under sustained axial loading, the compressive concrete creeps reduced the compressive stress in the concrete of the same model of short-term loading through time and increased on reinforcing steel.

Deformation of concrete slowly increases due to creep of concrete caused by sustained axial loading. As a result, concrete begins to crack and the axial load is shared to reinforcing steel. This makes reinforcing steel highly stressed and concrete part of column low stressed through time. This effect was accounted through concrete damaged plasticity model of tension stiffening concept and the results obtained from the finite element analysis confirmed that compressive stress decreases in concrete and increases on reinforcing steel through time as shown in Figure 5.7.

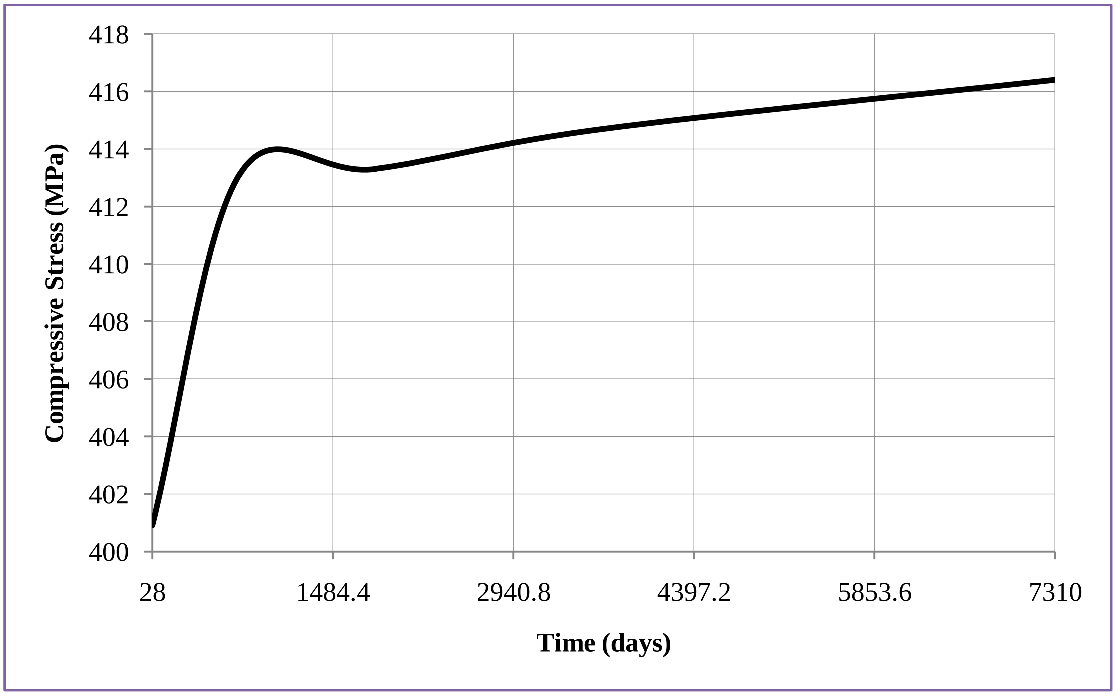

Figure 5.7: Time-dependent compressive stress on reinforcing steel

The percent increase of compressive stress on reinforcing steel with sustained time due to the effect of concrete creep is depicted in Figure 5.8.

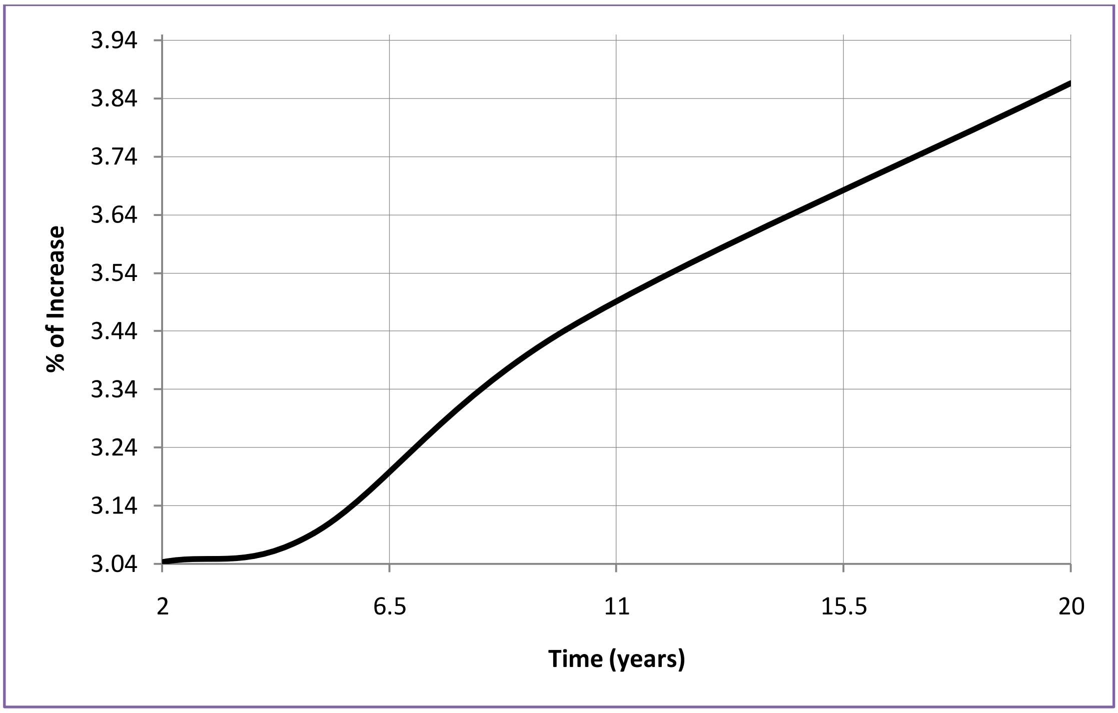

Figure 5.8: Percent of increase of compressive stress on reinforcement with time

Generally, from the performed finite element analysis results, on average the compressive concrete creep through time reduces the compressive stress in concrete obtained under short-term loading by about 85% and increases on reinforcing steel by 3 to 3.85%.

5.2.3 Strain in Concrete

Under sustained axial loading, any increase in the concrete strain of the analysis under short-term loading is due to accounted creep of concrete since the only considered time-dependent effect in concrete was a concrete creep. Figure 5.9 shows the node and element number of maximum principal strain in concrete under short-term loading at the finite element analysis increment where peak compressive stress in concrete is obtained. For the analysis under sustained axial loading of different durations, the contour visualizations of the maximum principal strain in concrete at the increment of peak compressive stress in concrete are shown in Appendix C.

The highlighted point shows the node of maximum principal strain in concrete for short-term loading analysis.

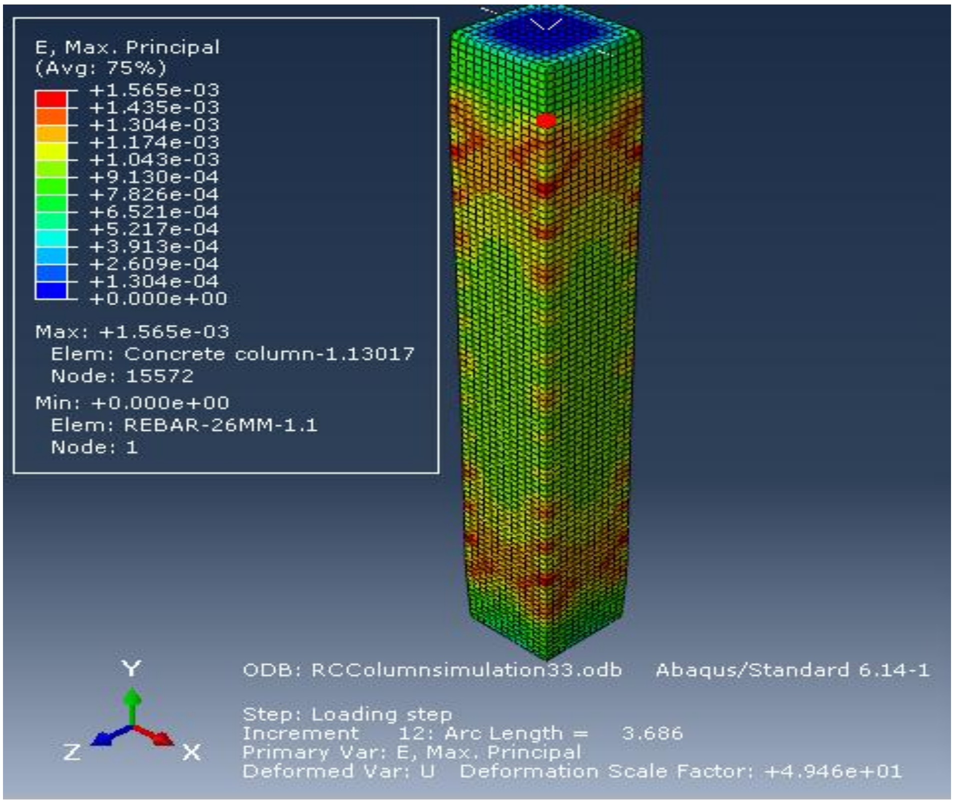

Figure 5.9: Maximum principal strain in concrete column (t=28 days)

The time-dependent strain in concrete for a model of different loading duration is depicted by taking the maximum value of principal strain in concrete at the increment where peak compressive stress in concrete is obtained and shown in Figure 5.10.

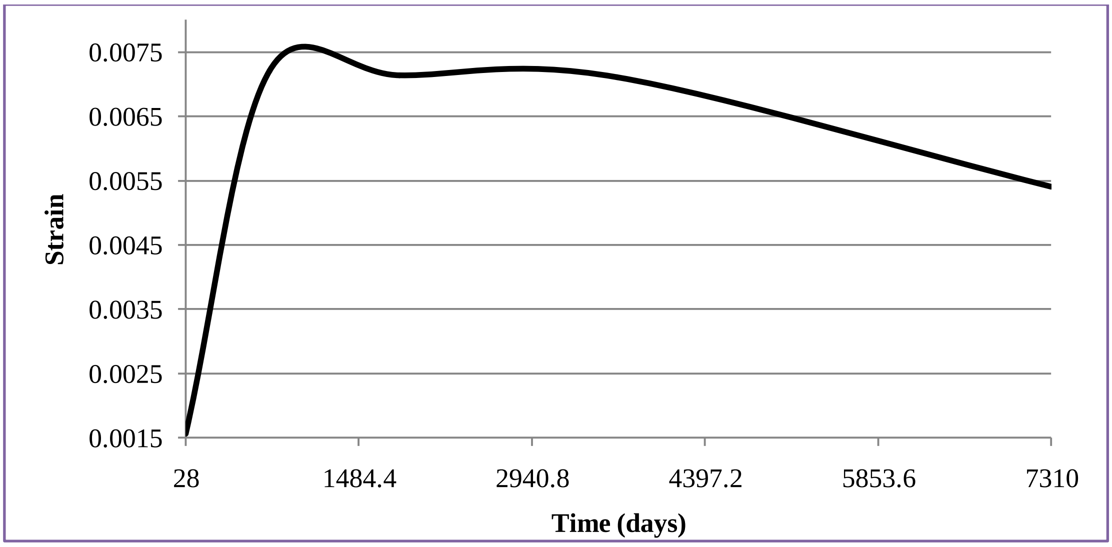

Figure 5.10: Strain in the concrete column with time

The obtained results show that compressive creep of concrete due to sustained axial loading increased strain in the concrete part of the column up to 2 years and after that decreases. This was due to compressive stress increases on reinforcement and decreases in concrete through time as discussed in section 5.2.1. This makes concrete part of column low stressed through time and strain in it decreases gradually.

5.2.4 Stress-Strain Response in Concrete

The time-dependent compressive stress-strain relationship in the concrete of reinforced concrete column under sustained axial loading is shown in Figure 5.11.

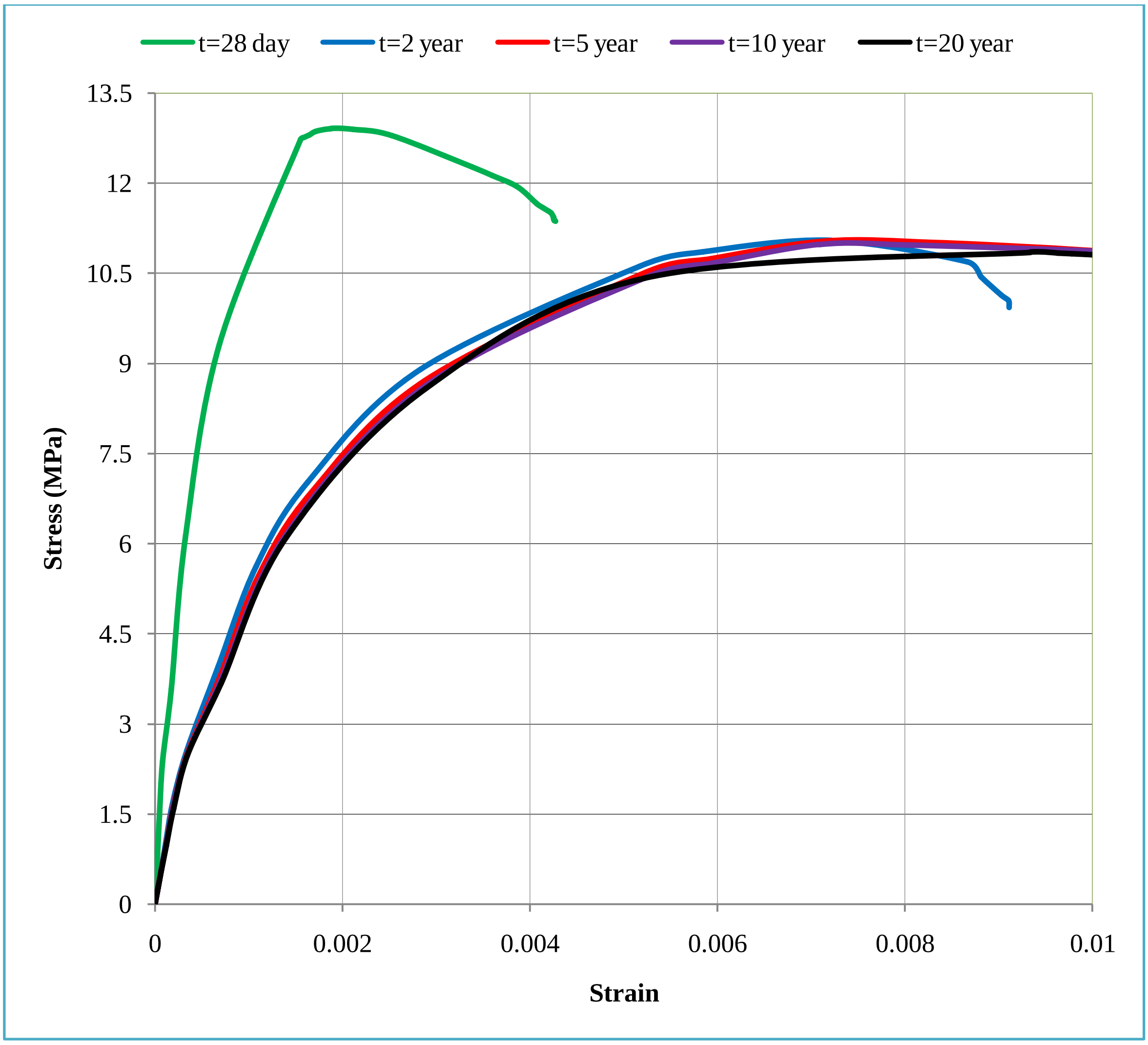

Figure 5.11: Compressive stress-strain relationship in a concrete column

The compressive creep of concrete due to sustained axial loading reduced gradually the obtained compressive stress in concrete under the analysis of short-term loading by about 85% as presented in section 5.2.2. Creep of concrete delays the strain at which peak compressive stress in concrete is obtained.

5.2.5 Concrete Damage

The parts affected due to compressive and tensile damage of concrete in the time-dependent analysis of reinforced concrete column were simulated in ABAQUS. For discussions, the concrete damage at the last increment of finite element analysis clearly shows the parts of the column which highly affected by compression and tension. From the performed finite element simulations for different durations of axial loading, 5 and 10 years loading durations are presented in this section. For the other loading durations, it is shown in Appendix C.

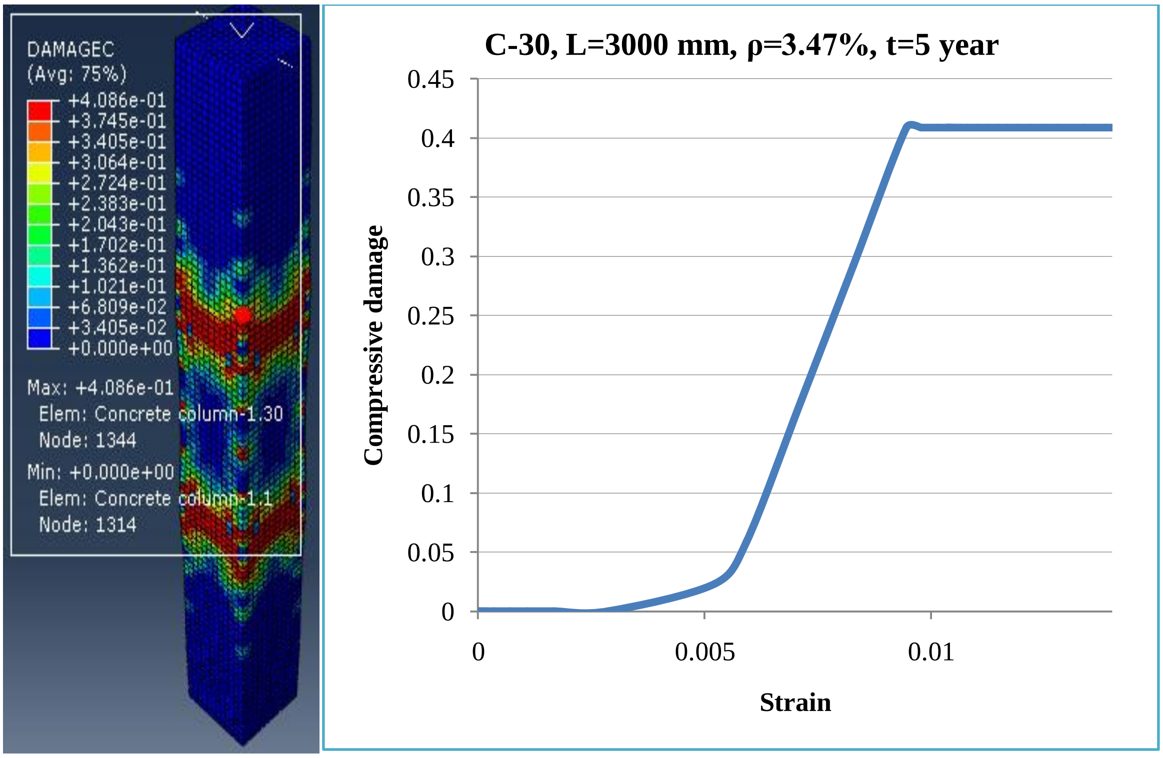

Figure 5.12: Compression damage (t=5 year)

The part of the column damaged by tension was around the highlighted point.

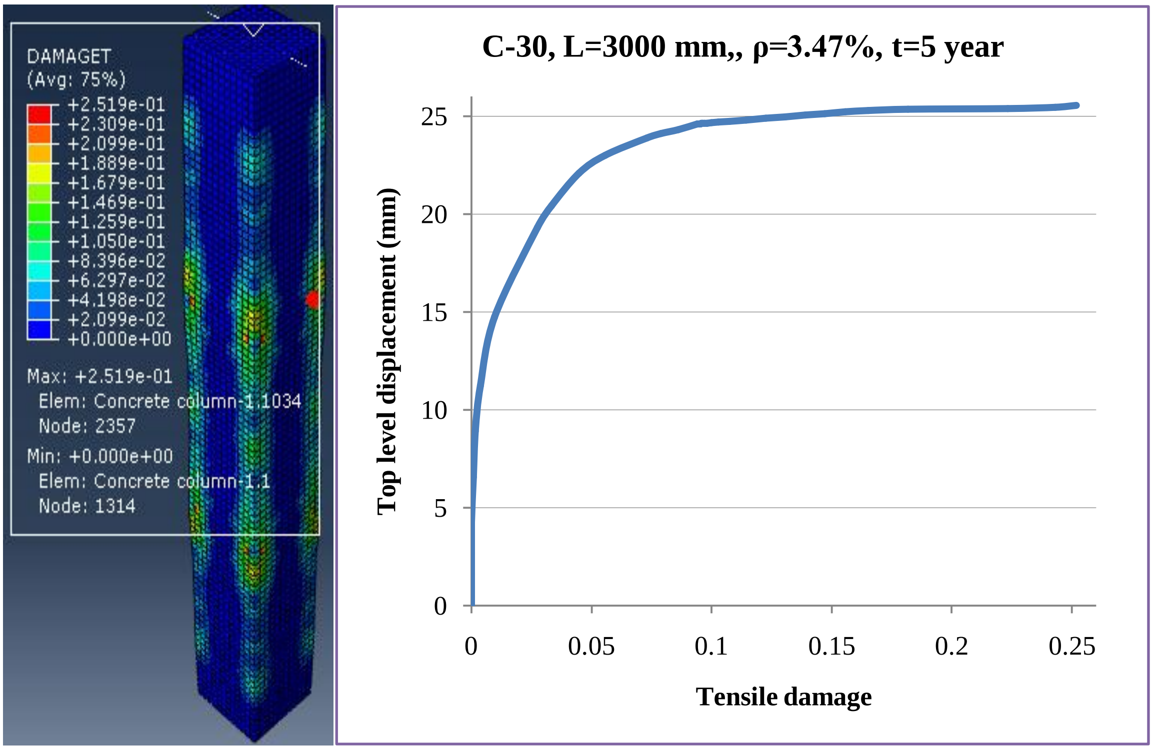

Figure 5.13: Tension damage (t=5 year)

As the duration of load increases, more area of the concrete column is damaged by compression and tension under sustained axial loading.

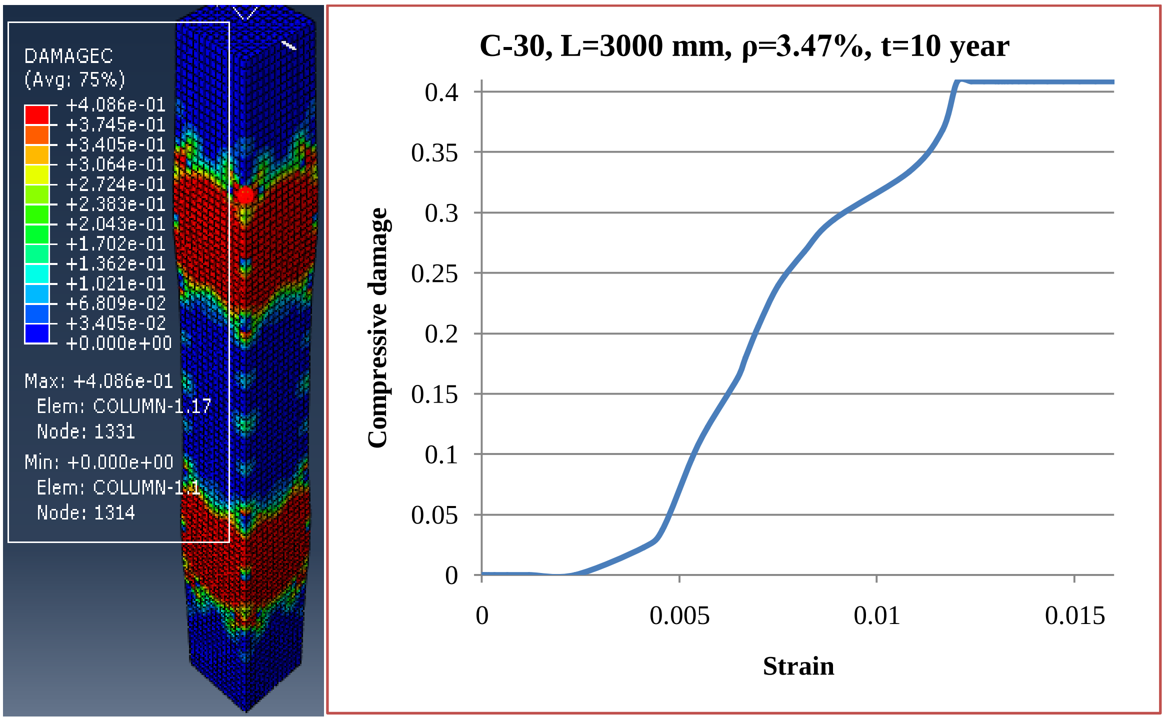

Figure 5.14: Compression damage (t=10 year)

Due to tension damage of concrete, around the highlighted part of the column is affected.

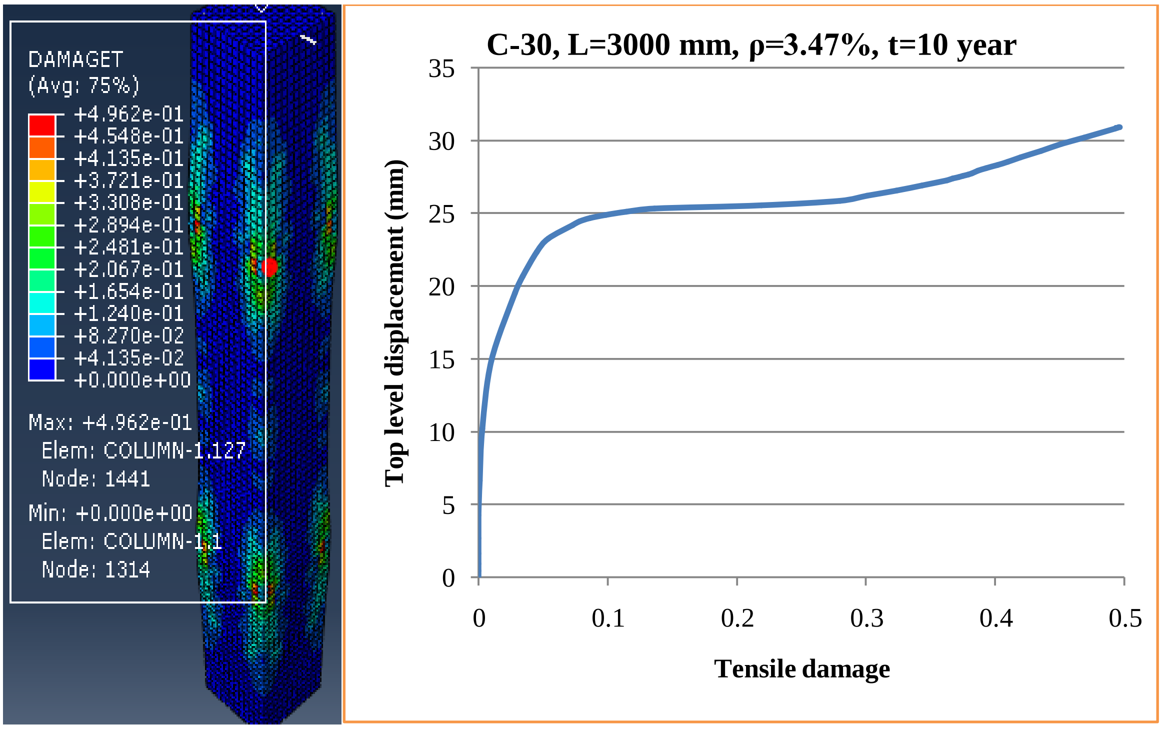

Figure 5.13: Tension damage (t=10 year)

As can be seen from the contour visualization, the parts of the reinforced concrete column damaged due to compression and tension are at some distance from the top and bottom part of the column. As the duration of sustained axial loading increases, wide parts of concrete columns are damaged by compression and tension. Creep of concrete contributes much to compression damage. This was due to compressive concrete creep is accounted in compressive behavior of concrete damaged plasticity model used for concrete material modeling.

5.3 Parametric Study

Finite element analyses were carried out in order to study the effects of different parameters on concrete creep which contributes to the strain of the concrete column. To carry out the parametric study, except the study parameter the others are kept constant. The response is simulated under sustained axial loading of magnitude 3000 kN.

Under sustained axial loading of different durations, any increase in the concrete strain of under the analysis of short-term loading is due to creep of concrete because the considered time-dependent effect in concrete is the only compressive creep of concrete. The effect of parameters studied in this research includes reinforcement ratios, concrete grade, and column lengths. Figure 5.14 shows the comparison of the effect of concrete creep in increasing the concrete strain under short-term analysis for different durations of loading.

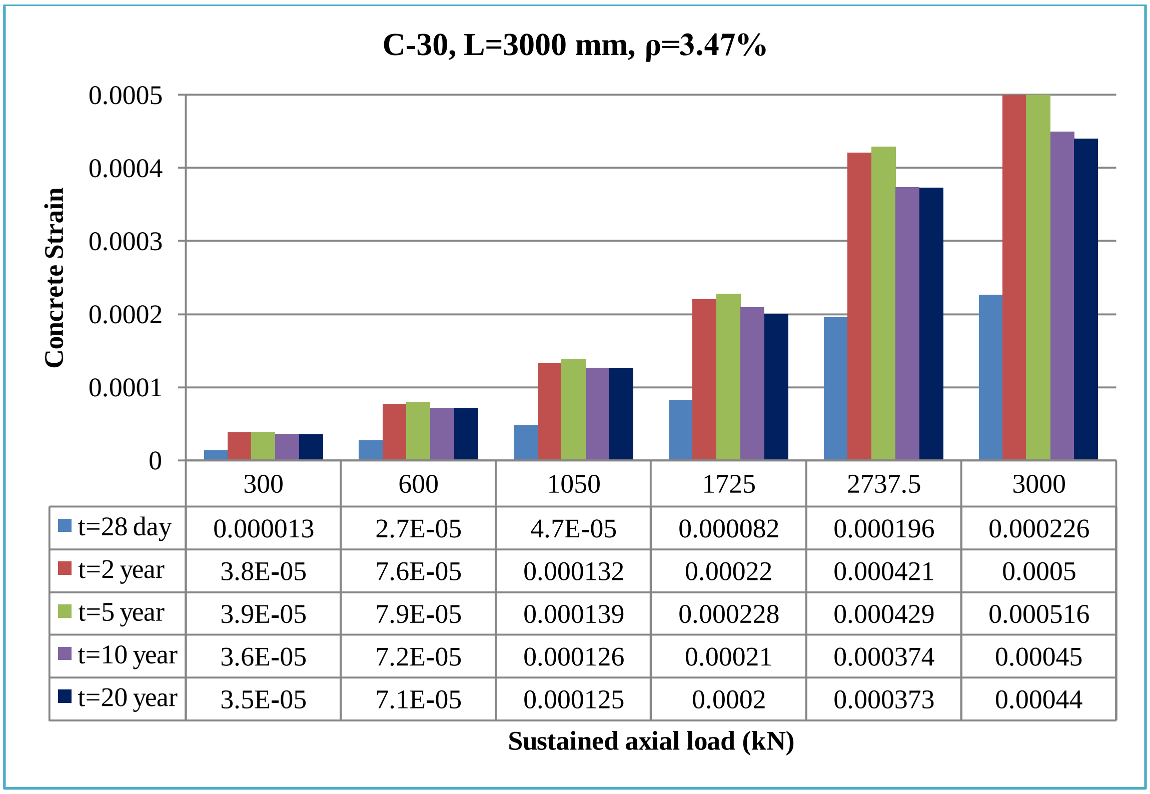

Figure 5.14: Time-dependent concrete strain with strain under short-term analysis

5.3.1 Effect of Reinforcement Ratio

Keeping other parameters constant, the effect of longitudinal reinforcement ratio of 0.83%, 1.86%, and 3.47% on the time-dependent strain in concrete due to creep of concrete were studied. The effect of reinforcement ratio for 3000 mm reinforced C-30 concrete column is presented. Figure 5.15 shows the effect of reinforcement ratio on the time-dependent response of maximum principal strain in concrete under sustained axial loading.

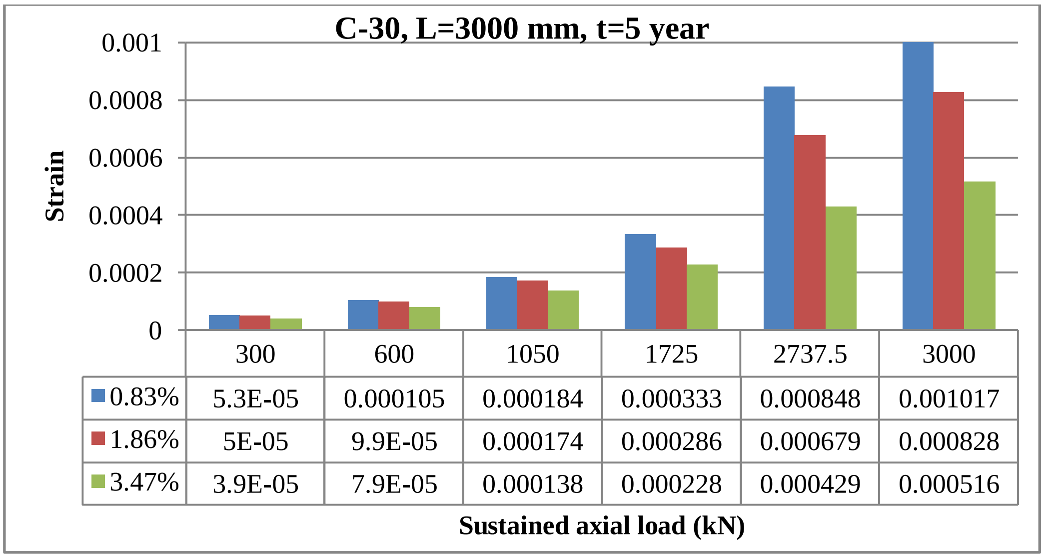

Figure 5.15: Concrete strain for different reinforcement ratio

As reinforcement ratio increases, the time-dependent principal strain developed in concrete due to concrete creep decreases. Therefore, by providing a maximum area of longitudinal reinforcement, creep strain of concrete is significantly reduced.

5.3.2 Effect of Concrete Grade

Keeping other parameters constant, the effects of concrete grade on the time-dependent principal strain developed in the concrete column due to the contribution of concrete creep were presented. Graphically, the effect of concrete grade on the contribution of creep in principal concrete strain is shown in Figure 5.16.

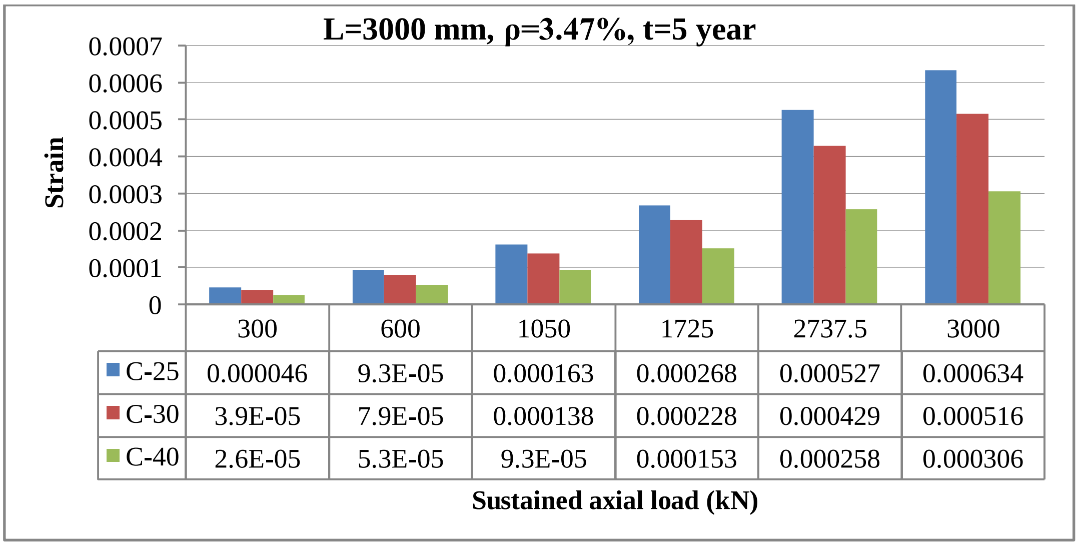

Figure 5.16: Concrete strain for different concrete grade

From Figure 5.16, concrete strain mainly due to concrete creep under sustained axial loading decreases as concrete grade increases. Therefore, the effect of concrete creep contribution on the strain developed in the concrete column is significantly reduced by using concrete which has high compressive strength.

5.3.3 Effect of Column Length

Figure 5.17 depicts the effect of column length on the principal strain developed in the concrete column.

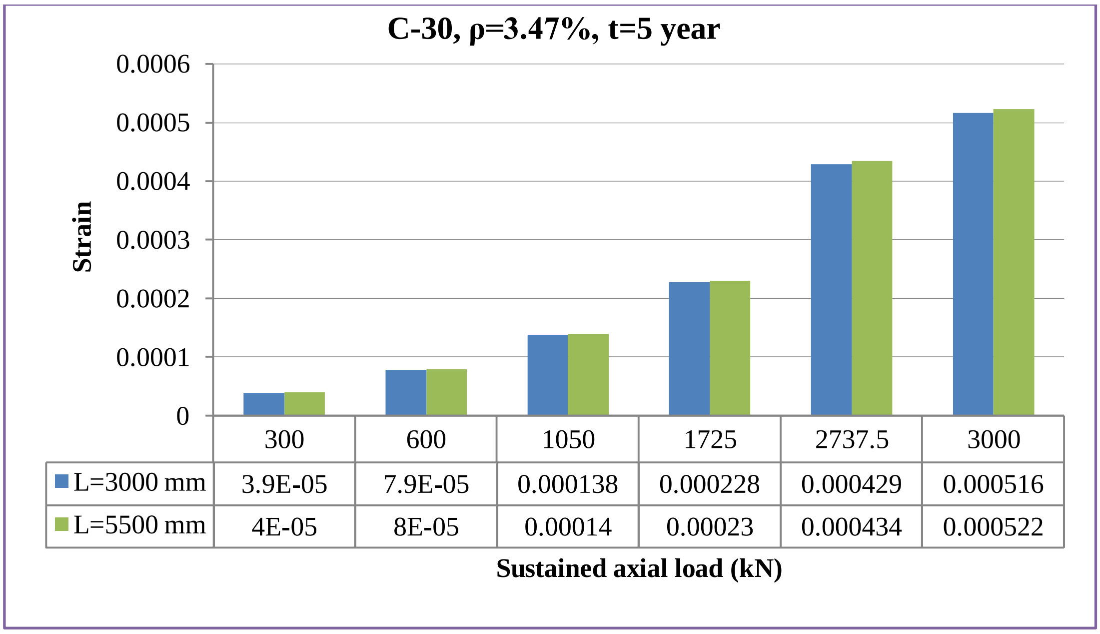

Figure 5.17: Concrete strain for different column length

From the finite element analysis results, under concentrically applied sustained axial loading, increasing length of the column increases the concrete strain by a very small value. This might be due to not considering geometric nonlinearity.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The nonlinear finite element analyses of the time-dependent response of pin-ended reinforced concrete columns under concentrically applied sustained axial load through ABAQUS 6.14-1 were successfully accomplished. The obtained results for the ultimate strength of reinforced concrete column from ABAQUS 6.14-1 were compared with the ACI 318-14 equation calculation and recommendation of Westerberg (2008) for validation and very good accuracy was obtained with difference less than 2.5%. The concrete damaged plasticity model used for modeling concrete and the concrete creep accounted in the concrete model according to the recommendation of Es En-2 were capable of simulating the effect of concentrically applied sustained axial load on pin-ended reinforced concrete columns.

From analysis results due to sustained axial loading, creep of concrete does not affect the load-carrying capacity of the reinforced concrete column. It distributes the load from concrete to reinforcing steel through time. Creep of concrete increases the vertical displacement of concrete columns which increases strain in concrete that makes concrete deforms. As a result, the load is transferred to reinforcing steel and compressive stress increases on reinforcing steel and decreases in concrete. This effect was accounted through concrete damaged plasticity model for concrete tension stiffening. Generally, on average, the compressive concrete creeps reduced the compressive stress in the concrete of reinforced concrete column under short-term loading analysis by about 85% and it increased the compressive stress on reinforcing steel by 3 to 3.85%. Also, concrete creep under sustained axial loading slowly decreases the compressive stress in concrete within a sustained period of time. The difference in stress reduction between sustained periods of time is very small.

From the performed parametric study, it was found that the strain in concrete mainly due to creep of concrete was significantly influenced by concrete grade and longitudinal reinforcement ratio and the following conclusions can be given.

- Increase in concrete strength significantly reduces the creep strain of concrete and obviously increase the capacity of reinforced concrete columns.
- Reinforcement ratio significantly reduces creep strain of concrete and obviously increases the strength of reinforced concrete columns.
- Without considering geometric nonlinearity of materials which might happen, an increase in the length of column increase displacement and strain in concrete by a small value.

6.2 Recommendations and Future Works

From the analysis results of this research, the ultimate strength of reinforced concrete column best agrees with the conclusion of Westerberg (2008) which states that the better agreement of strength analysis with test results was obtained without the normal conversion factor 0.85 for concrete. Further research can be performed on this using another technique of material modeling to verify it.

This thesis may be an input for further research. Future works can be performed in the following area.

- To support and validate the time-dependent analysis of this research, the experimental study can be performed.
- The effects of eccentric sustained loading on pin-ended reinforced concrete columns considering geometric nonlinearity can be studied.
- The contribution of concrete creep on the buckling response of pin-ended reinforced concrete long columns can be studied.

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APPENDIX A: Input Data in Concrete Damaged Plasticity Model

Table A.1: Summary of C-25 concrete damaged plasticity model (t=28 days)

Compressive Behavior		**Compression Damage**		
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Damage Parameter (d_c)	Inelastic Strain (ε_c^{in})	
9.9	0	0	0	
12.622	2.998E-05	0	2.998E-05	
22.096	0.00016	0	0.00016	
28.556	0.000386	0	0.000386	
32.133	0.000703	0	0.000703	
33	0.001021	0	0.001021	
32.947	0.001108	0.002	0.001108	
31.686	0.001493	0.040	0.001493	
22.538	0.002584	0.317	0.002584	
18.950	0.002898	0.426	0.002898	
Tensile Behavior		**Tension Damage**		
Yield Stress (MPa)	Displacement (mm)	Damage Parameter (d_t)	Displacement (mm)	
2.565	0	0	0	
1.309	0.028	0.490	0.028	
0.765	0.055	0.702	0.055	
0.533	0.082	0.792	0.082	
0.409	0.110	0.841	0.110	
0.315	0.138	0.877	0.138	
0.231	0.165	0.910	0.165	
0.156	0.192	0.940	0.192	
0.092	0.220	0.964	0.220	
0.040	0.248	0.984	0.248	
0.006	0.27	0.998	0.27	
Plasticity Parameters				
Dilation Angle	Eccentricity	$\frac{f_{bo}}{f_{co}}$	K	Viscosity Parameter
30˚	0.1	1.16	0.667	0

Table A.2: Summary of C-25 stress-strain values accounting concrete creep

Compressive Behavior			
For t=2 years		For t=5 years	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
9.9	0	9.9	0
12.622	0.000126	12.622	0.000135
22.096	0.000672	22.096	0.000720
28.556	0.001620	28.556	0.001735
32.133	0.00295	32.133	0.003162
33	0.00429	33	0.004592
32.947	0.004653	32.947	0.004984
31.686	0.006271	31.686	0.006716
22.538	0.010851	22.538	0.011622
18.950	0.012169	18.950	0.013034
For t=10 years		For t=20 years	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
9.9	0	9.9	0
12.622	0.000139	12.622	0.000141
22.096	0.000740	22.096	0.000751
28.556	0.001784	28.556	0.001811
32.133	0.003251	32.133	0.003301
33	0.004721	33	0.004793
32.947	0.005125	32.947	0.005203
31.686	0.006906	31.686	0.007011
22.538	0.011949	22.538	0.012131
18.950	0.013401	18.950	0.013606

Table A.3: Summary of C-30 concrete damaged plasticity model (t=28 days)

Compressive Behavior		**Compression Damage**	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Damage Parameter (d_c)	Inelastic Strain (ε_c^{in})
11.4	0	0	0
13.453	2.13E-05	0	2.13E-05
24.049	0.000130	0	0.000130
31.717	0.000327	0	0.000327
36.392	0.000616	0	0.000616
38	0.0010	0	0.0010
37.838	0.001148	0.0042	0.001148
36.364	0.001492	0.0431	0.001492
26.811	0.002483	0.2944	0.002483
22.474	0.002815	0.4086	0.002815
Tensile Behavior		**Tension Damage**	
Yield Stress (MPa)	Displacement (mm)	Damage Parameter (d_t)	Displacement (mm)
2.896	0	0	0
1.389	0.0275	0.521	0.0275
0.792	0.055	0.726	0.055
0.552	0.0825	0.809	0.0825
0.417	0.11	0.856	0.11
0.307	0.1375	0.894	0.1375
0.208	0.165	0.928	0.165
0.123	0.1925	0.957	0.1925
0.055	0.22	0.981	0.22
0.0005	0.249	0.999	0.249

Plasticity Parameters				
Dilation Angle	Eccentricity	$\frac{f_{bo}}{f_{co}}$	K	Viscosity Parameter
30˚	0.1	1.16	0.6667	0

Table A.4: Summary of C-30 stress-strain values accounting concrete creep

Compressive Behavior			
For t=2 years		**For t=5 years**	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
11.4	0	11.4	0
13.453	7.41E-05	13.453	7.90E-05
24.048	0.000451	24.048	0.000481
31.717	0.001138	31.717	0.001213
36.392	0.002143	36.392	0.002284
38	0.003497	38	0.003726
37.838	0.003995	37.838	0.004256
36.364	0.005195	36.364	0.005536
26.811	0.008644	26.811	0.009211
22.474	0.00980	22.474	0.010442
For t=10 years		**For t=20 years**	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
11.4	0	11.4	0
13.453	8.11E-05	13.453	8.22E-05
24.048	0.000493	24.048	0.00050
31.717	0.001245	31.717	0.001262
36.392	0.002343	36.392	0.002376
38	0.003823	38	0.003877
37.838	0.004367	37.838	0.004429
36.364	0.005680	36.364	0.005760
26.811	0.009451	26.811	0.009584
22.474	0.010714	22.474	0.010865

Table A.5: Summary of C-40 concrete damaged plasticity model (t=28 days)

Compressive Behavior		**Compression Damage**		
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Damage Parameter (d_c)		Inelastic Strain (ε_c^{in})
14.4	0	0		0
14.865	8.93E-06	0		8.93E-06
27.403	8.40E-05	0		8.40E-05
37.305	0.000234	0		0.000234
44.210	0.000469	0		0.000469
47.684	0.000801	0		0.000801
48	0.000961	0		0.000961
47.646	0.001147	0.007		0.001147
42.441	0.001795	0.116		0.001795
35.964	0.002279	0.251		0.002279
30.064	0.002646	0.374		0.002646
Tensile Behavior		**Tension Damage**		
Yield Stress (MPa)	Displacement (mm)	Damage Parameter (d_t)		Displacement (mm)
3.509	0	0		0
1.514	0.0275	0.5686		0.0275
0.840	0.055	0.7607		0.055
0.582	0.0825	0.8340		0.0825
0.417	0.11	0.8811		0.11
0.274	0.1375	0.9219		0.1375
0.152	0.165	0.9566		0.165
0.057	0.1925	0.9836		0.1925
0.0015	0.214	0.9996		0.214
Plasticity Parameters				
Dilation Angle	Eccentricity	$\frac{f_{bo}}{f_{co}}$	K	Viscosity Parameter
30˚	0.1	1.16	0.6667	0

Table A.6: Summary of C-40 stress-strain values accounting concrete creep

Compressive Behavior			
For t=2 years		**For t=5 years**	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
14.4	0	14.4	0
14.865	2.35E-05	14.865	2.48E-05
27.403	0.000221	27.403	0.000233
37.305	0.000615	37.305	0.000648
44.210	0.001232	44.210	0.00130
47.684	0.002106	47.684	0.002222
48	0.002528	48	0.002666
47.646	0.003016	47.646	0.003182
42.441	0.004720	42.441	0.004978
35.964	0.005992	35.964	0.006320
30.064	0.006958	30.064	0.007340
For t=10 years		**For t=20 years**	
Yield Stress (MPa)	Inelastic Strain (ε_c^{in})	Yield Stress (MPa)	Inelastic Strain (ε_c^{in})
14.4	0	14.4	0
14.865	2.53E-05	14.865	2.56E-05
27.403	0.000238	27.403	0.000241
37.305	0.000662	37.305	0.000670
44.210	0.001328	44.210	0.001344
47.684	0.002270	47.684	0.002297
48	0.002724	48	0.002756
47.646	0.003251	47.646	0.003289
42.441	0.005087	42.441	0.005147
35.964	0.006458	35.964	0.006534
30.064	0.007499	30.064	0.007588

APPENDIX B: Element Type and Meshing Used in Modeling

Table B.1: Type and number of elements used in modeling 5500 mm length column

Part	Element type	No.of elements	No. of nodes
ConcreteColumn	Hex(C3D8R)	26352	31096
Rebars	Truss(T3D2)	183	184
Stirrups	Truss(T3D2)	116	116

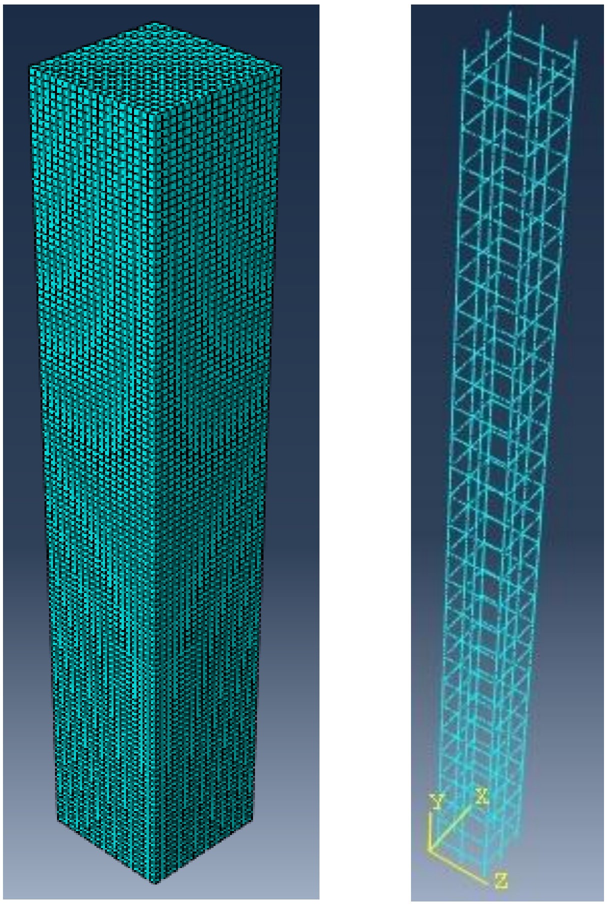


Figure B.1: Meshing of the modeled column for 5500 mm length

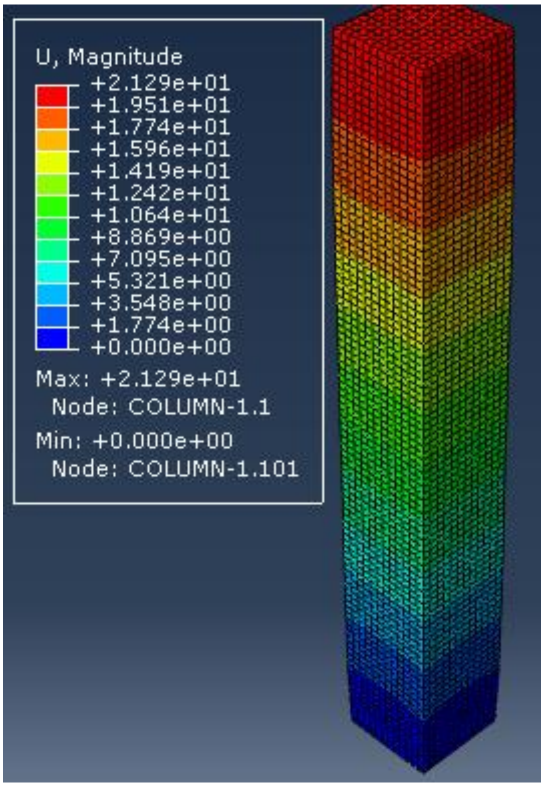
APPENDIX C: Simulation Results

Table C.1: Summary of simulation results for different parameters

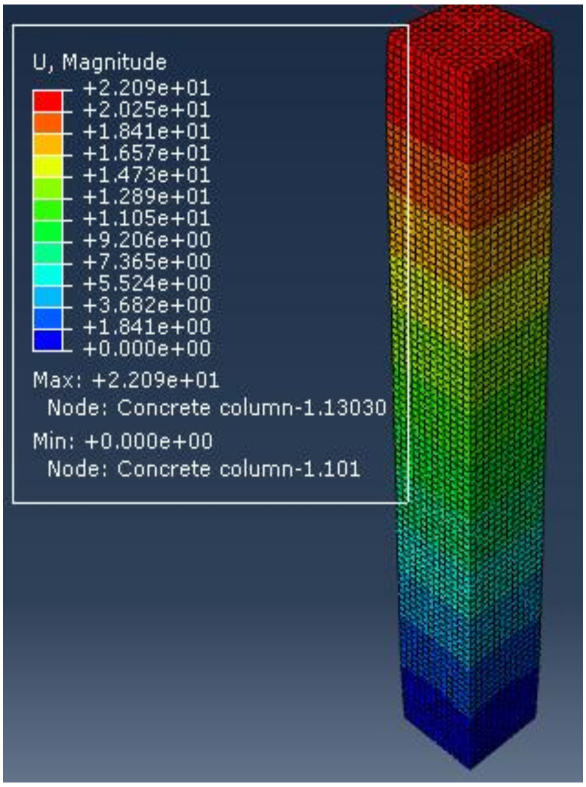
Model	Grade	Column dimension (mm)	ρ (%)	P_u (kN)	$\sigma_{c,Max}$ (MPa)	σ_s (MPa)	Loading duration
1	C-25	350 x 350 x 3000	0.83	4309	10.80	400.2	t=28 day
2	C-25	350 x 350 x 3000	1.86	4764	11.30	400.8	t=28 day
3	C-25	350 x 350 x 3000	3.47	5523	12.01	401.0	t=28 day
4	C-25	350 x 350 x 3000	0.83	4245	9.853	415.9	t=2 year
5	C-25	350 x 350 x 3000	1.86	4766	9.932	416.0	t=2 year
6	C-25	350 x 350 x 3000	3.47	5583	10.05	415.0	t=2 year
7	C-25	350 x 350 x 3000	0.83	4241	9.830	416.2	t=5 year
8	C-25	350 x 350 x 3000	1.86	4771	9.965	417.0	t=5 year
9	C-25	350 x 350 x 3000	3.47	5561	9.916	418.4	t=5 year
10	C-25	350 x 350 x 3000	0.83	4240	9.823	416.6	t=10 year
11	C-25	350 x 350 x 3000	1.86	4774	9.961	417.5	t=10 year
12	C-25	350 x 350 x 3000	3.47	5586	10.04	416.7	t=10 year
13	C-25	350 x 350 x 3000	0.83	4239	9.824	416.8	t=20 year
14	C-25	350 x 350 x 3000	1.86	4774	9.959	417.6	t=20 year
15	C-25	350 x 350 x 3000	3.47	5584	10.04	418.0	t=20 year
16	C-25	350 x 350 x 5500	0.83	4311	10.82	400.7	t=28 day
17	C-25	350 x 350 x 5500	1.86	4754	11.29	401.4	t=28 day
18	C-25	350 x 350 x 5500	3.47	5527	12.06	400.7	t=28 day
19	C-25	350 x 350 x 5500	0.83	4252	9.886	416.1	t=2 year
20	C-25	350 x 350 x 5500	1.86	4776	9.956	415.6	t=2 year
21	C-25	350 x 350 x 5500	3.47	5588	10.06	415.3	t=2 year
22	C-25	350 x 350 x 5500	0.83	4245	9.842	416.0	t=5 year
23	C-25	350 x 350 x 5500	1.86	4775	9.979	416.9	t=5 year
24	C-25	350 x 350 x 5500	3.47	5591	10.06	416.2	t=5 year
25	C-25	350 x 350 x 5500	0.83	4251	9.889	417.9	t=10 year
26	C-25	350 x 350 x 5500	1.86	4779	9.975	417.1	t=10 year
27	C-25	350 x 350 x 5500	3.47	5593	10.07	416.8	t=10 year
28	C-25	350 x 350 x 5500	0.83	4252	9.891	418.3	t=20 year

29	C-25	350 x 350 x 5500	1.86	4780	9.980	418.0	t=20 year
30	C-25	350 x 350 x 5500	3.47	5592	10.07	418.0	t=20 year
31	C-30	350 x 350 x 3000	0.83	4896	11.77	401.2	t=28 day
32	C-30	350 x 350 x 3000	1.86	5394	12.31	401.3	t=28 day
33	C-30	350 x 350 x 3000	3.47	6161	12.91	400.9	t= 28 day
34	C-30	350 x 350 x 3000	0.83	4831	10.88	412.9	t=2 year
35	C-30	350 x 350 x 3000	1.86	5347	10.94	412.8	t=2 year
36	C-30	350 x 350 x 3000	3.47	6153	11.05	413.1	t=2 year
37	C-30	350 x 350 x 3000	0.83	4825	10.84	413.6	t=5 year
38	C-30	350 x 350 x 3000	1.86	5343	10.91	413.4	t=5 year
39	C-30	350 x 350 x 3000	3.47	6155	11.04	413.3	t=5 year
40	C-30	350 x 350 x 3000	0.83	4824	10.83	414.0	t=10 year
41	C-30	350 x 350 x 3000	1.86	5339	10.88	413.6	t=10 year
42	C-30	350 x 350 x 3000	3.47	6150	10.98	413.4	t=10 year
43	C-30	350 x 350 x 3000	0.83	4823	10.82	414.2	t=20 year
44	C-30	350 x 350 x 3000	1.86	5337	10.87	413.7	t=20 year
45	C-30	350 x 350 x 3000	3.47	6125	10.85	416.4	t=20 year
46	C-30	350 x 350 x 5500	0.83	4904	11.84	400.8	t=28 day
47	C-30	350 x 350 x 5500	1.86	5393	12.37	400.9	t=28 day
48	C-30	350 x 350 x 5500	3.47	6165	12.92	401.0	t=28 day
49	C-30	350 x 350 x 5500	0.83	4837	10.91	413.2	t=2 year
50	C-30	350 x 350 x 5500	1.86	5354	10.97	412.8	t=2 year
51	C-30	350 x 350 x 5500	3.47	6163	11.09	412.9	t=2 year
52	C-30	350 x 350 x 5500	0.83	4836	10.90	414.2	t=5 year
53	C-30	350 x 350 x 5500	1.86	5355	10.97	413.8	t=5 year
54	C-30	350 x 350 x 5500	3.47	6161	11.06	413.3	t=5 year
55	C-30	350 x 350 x 5500	0.83	4836	10.90	414.7	t=10 year
56	C-30	350 x 350 x 5500	1.86	5351	10.95	414.0	t=10 year
57	C-30	350 x 350 x 5500	3.47	6163	11.05	413.8	t=10 year
58	C-30	350 x 350 x 5500	0.83	4836	10.90	414.8	t=20 year
59	C-30	350 x 350 x 5500	1.86	5351	10.95	414.3	t=20 year
60	C-30	350 x 350 x 5500	3.47	6164	11.06	414.1	t=20 year

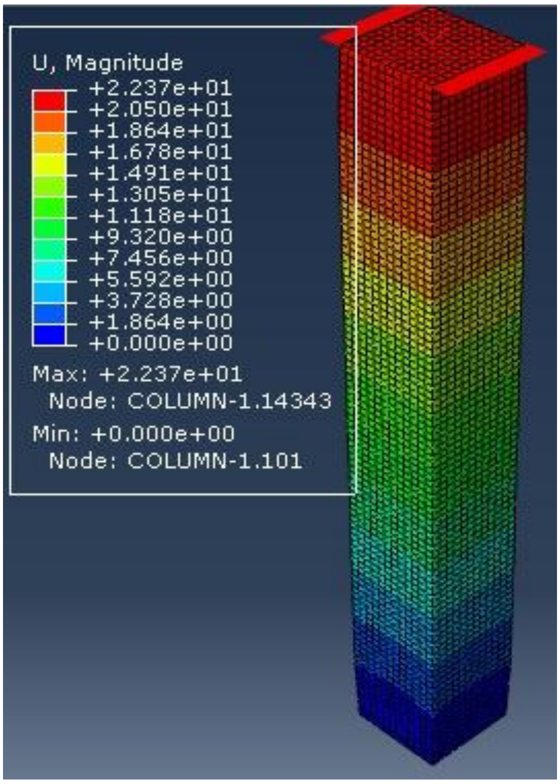
61	C-40	350 x 350 x 3000	0.83	6112	13.73	401.0	t=28 day
62	C-40	350 x 350 x 3000	1.86	6602	14.03	401.0	t=28 day
63	C-40	350 x 350 x 3000	3.47	7380	14.51	400.9	t= 28 day
64	C-40	350 x 350 x 3000	0.83	6018	13.01	409.0	t=2 year
65	C-40	350 x 350 x 3000	1.86	6521	13.0	409.5	t=2 year
66	C-40	350 x 350 x 3000	3.47	7335	13.11	408.8	t=2 year
67	C-40	350 x 350 x 3000	0.83	6014	12.99	409.6	t=5 year
68	C-40	350 x 350 x 3000	1.86	6479	12.83	411.7	t=5 year
69	C-40	350 x 350 x 3000	3.47	7335	13.13	409.8	t=5 year
70	C-40	350 x 350 x 3000	0.83	6012	12.98	409.8	t=10 year
71	C-40	350 x 350 x 3000	1.86	6479	12.83	412.1	t=10 year
72	C-40	350 x 350 x 3000	3.47	7332	13.11	410.0	t=10 year
73	C-40	350 x 350 x 3000	0.83	6011	12.98	409.9	t=20 year
74	C-40	350 x 350 x 3000	1.86	6529	13.04	410.2	t=20 year
75	C-40	350 x 350 x 3000	3.47	7333	13.11	410.1	t=20 year
76	C-40	350 x 350 x 5500	0.83	6116	13.75	400.9	t=28 day
77	C-40	350 x 350 x 5500	1.86	6606	14.03	400.8	t=28 day
78	C-40	350 x 350 x 5500	3.47	7374	14.47	401.3	t=28 day
79	C-40	350 x 350 x 5500	0.83	6023	13.05	409.6	t=2 year
80	C-40	350 x 350 x 5500	1.86	6540	13.07	408.9	t=2 year
81	C-40	350 x 350 x 5500	3.47	7343	13.16	409.2	t=2 year
82	C-40	350 x 350 x 5500	0.83	6022	13.03	409.9	t=5 year
83	C-40	350 x 350 x 5500	1.86	6536	13.07	409.6	t=5 year
84	C-40	350 x 350 x 5500	3.47	7342	13.16	409.9	t=5 year
85	C-40	350 x 350 x 5500	0.83	6018	13.02	409.9	t=10 year
86	C-40	350 x 350 x 5500	1.86	6533	13.06	410.6	t=10 year
87	C-40	350 x 350 x 5500	3.47	7340	13.16	410.2	t=10 year
88	C-40	350 x 350 x 5500	0.83	6017	13.02	410.6	t=20 year
89	C-40	350 x 350 x 5500	1.86	6534	13.07	410.2	t=20 year
90	C-40	350 x 350 x 5500	3.47	7340	13.15	410.3	t=20 year



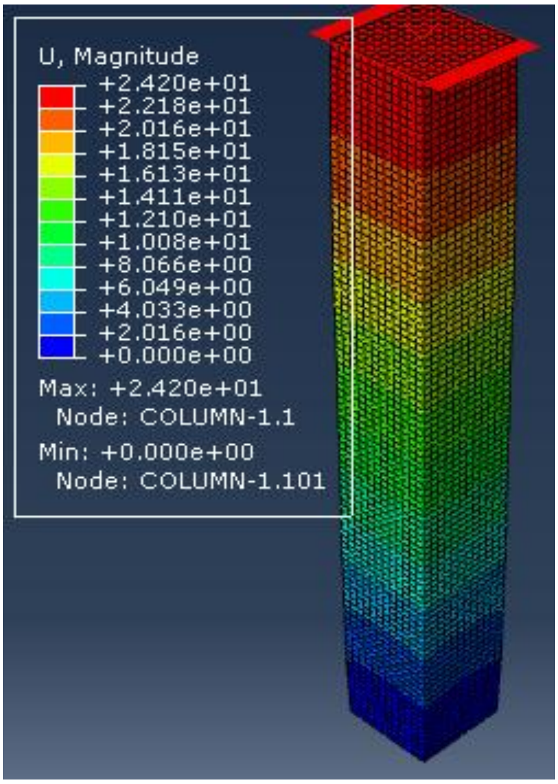
a) For t=2 year



b) For t=5 year

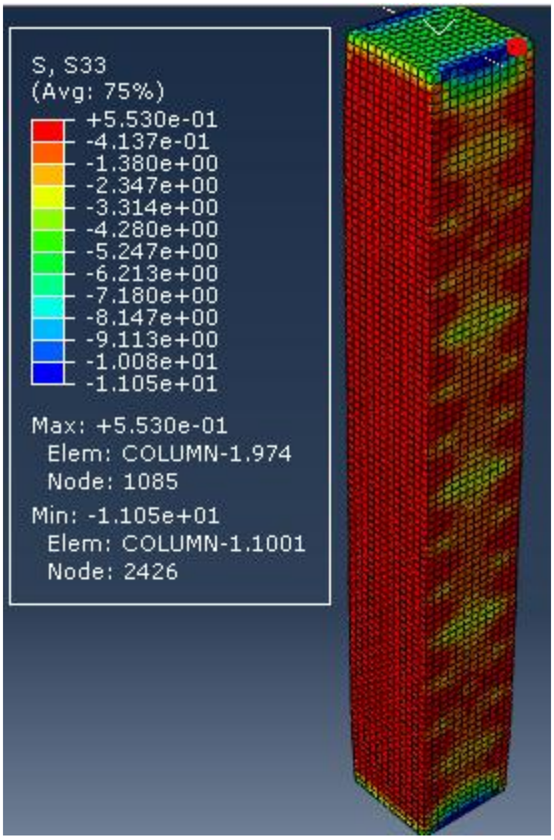


c) For t=10 year

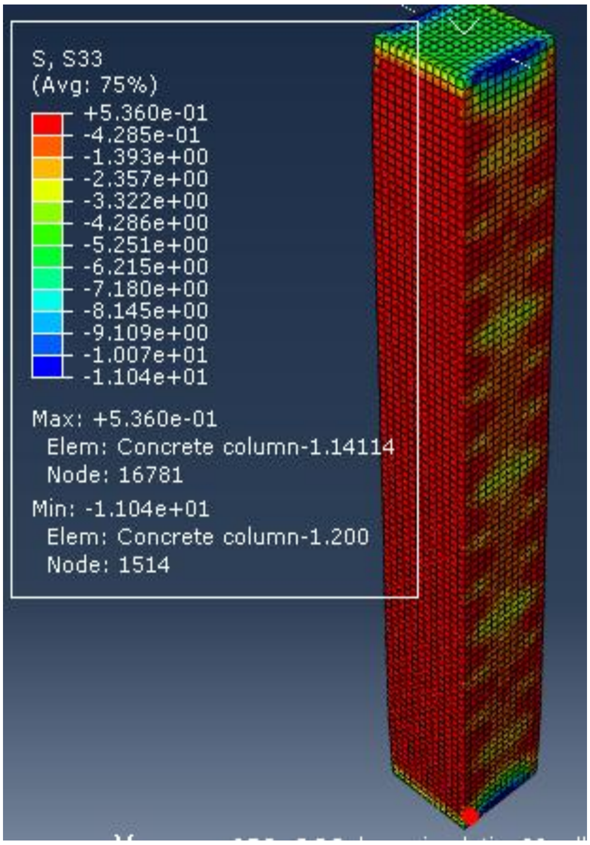


d) For t=20 year

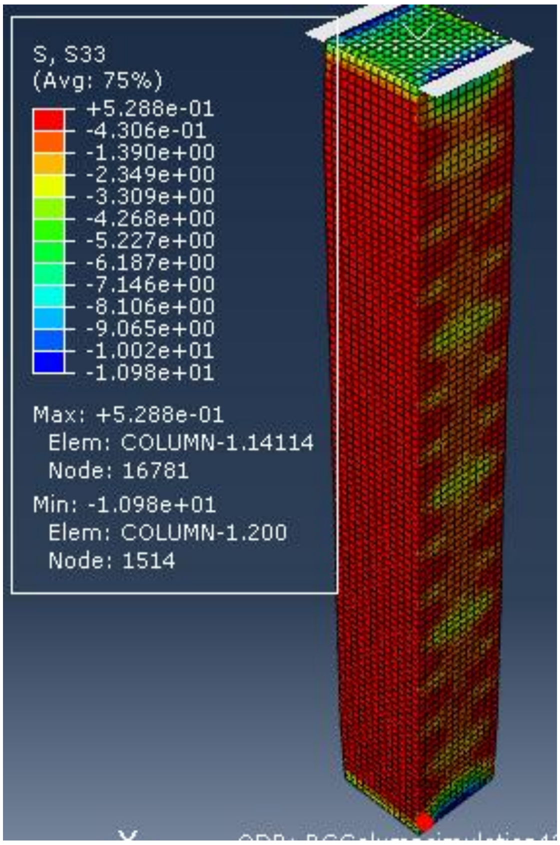
Figure C.1: Displacement at the increment where peak strength is obtained



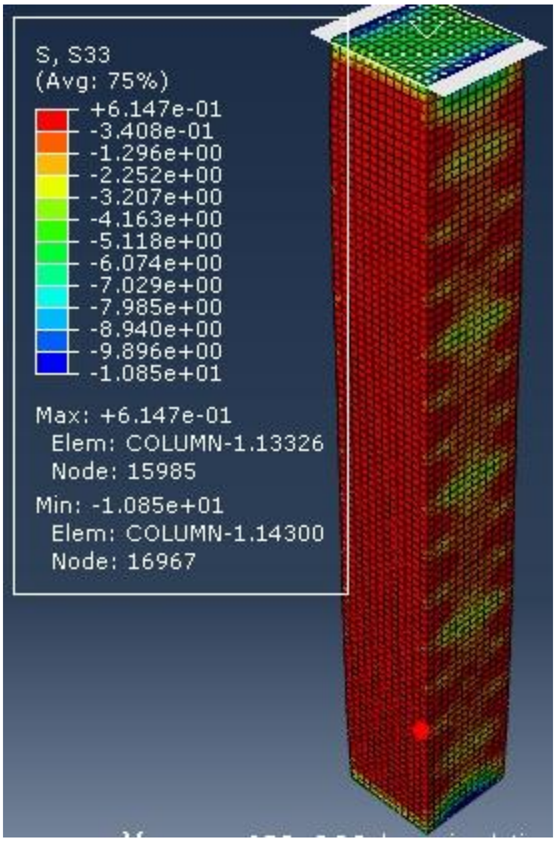
a) For t=2 years



b) For t=5 years

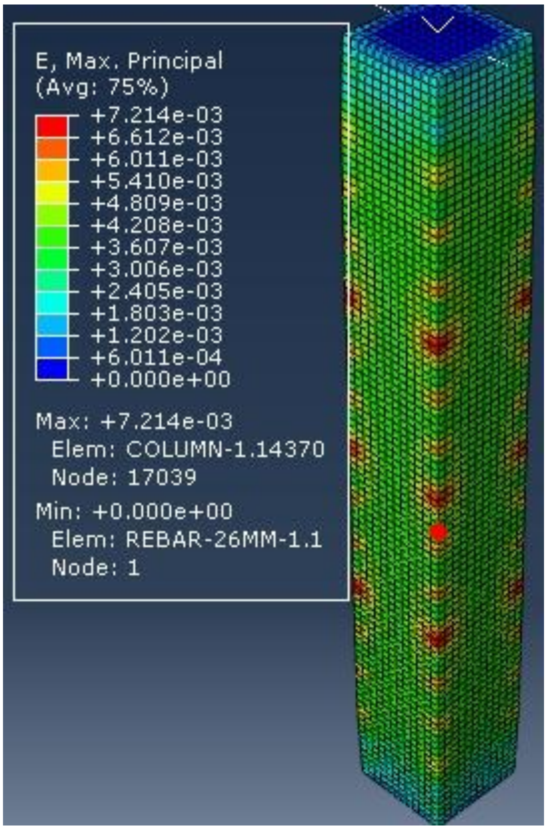


c) For t=10 years

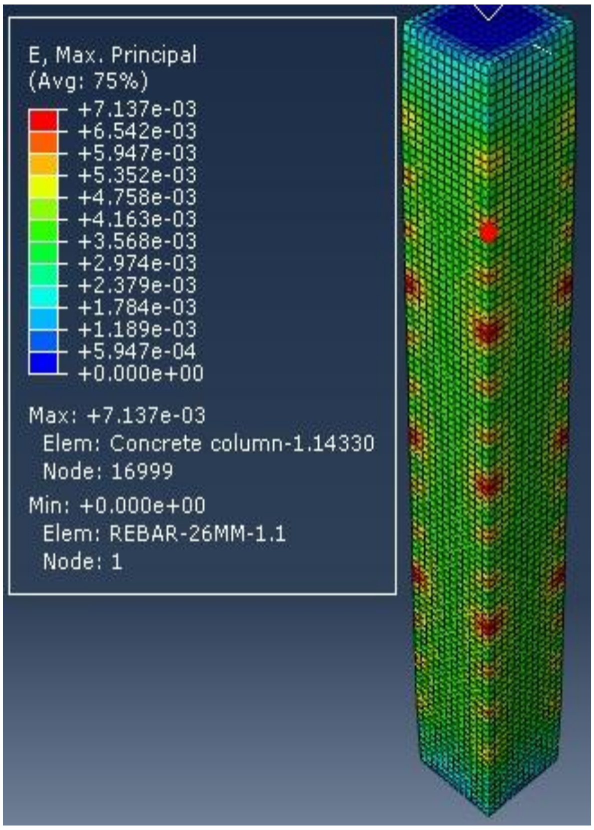


d) For t=20 years

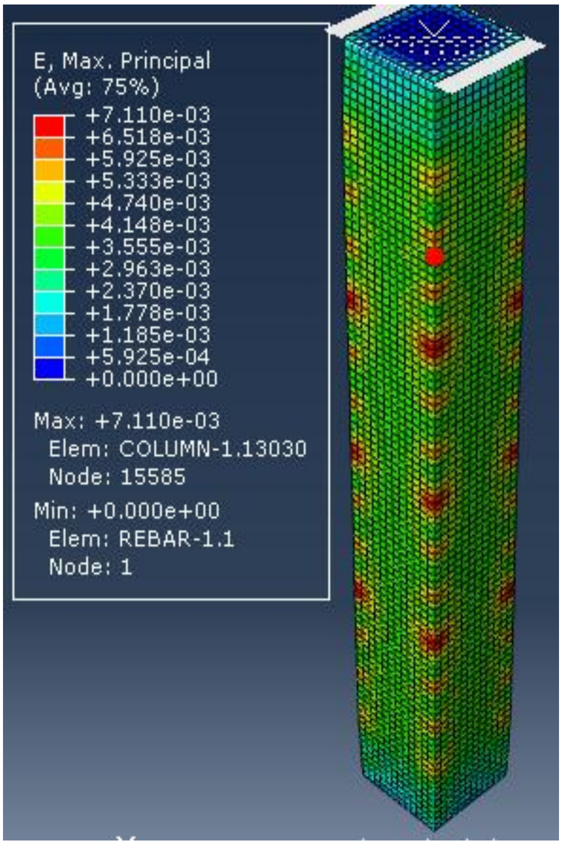
Figure C.2: Peak principal stress in C-30 concrete column for different time



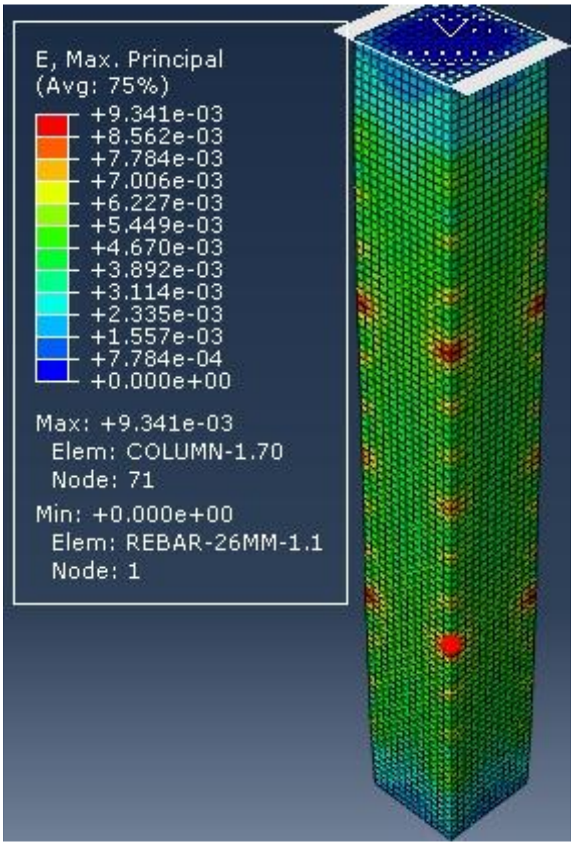
a) For t=2 years



b) For t=5 years



c) For t=10 years



d) For t=20 years

Figure C.3: Principal strain in C-30 concrete at peak stress in concrete

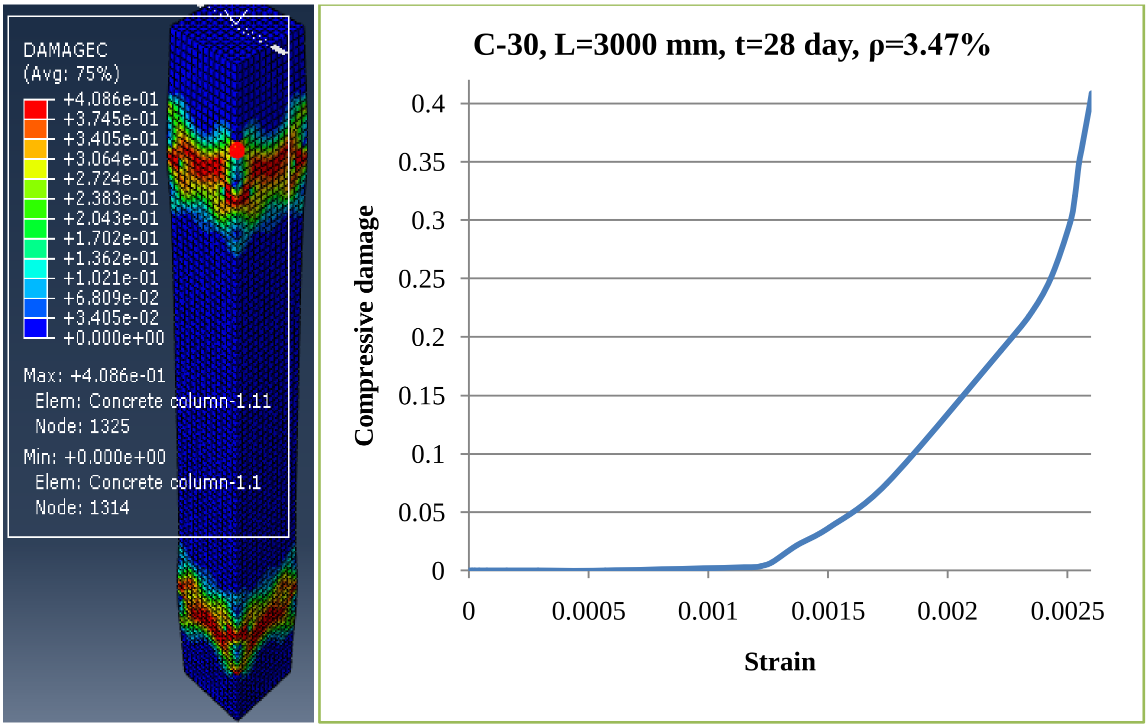


Figure C.4: Compression damage (t=28 days)

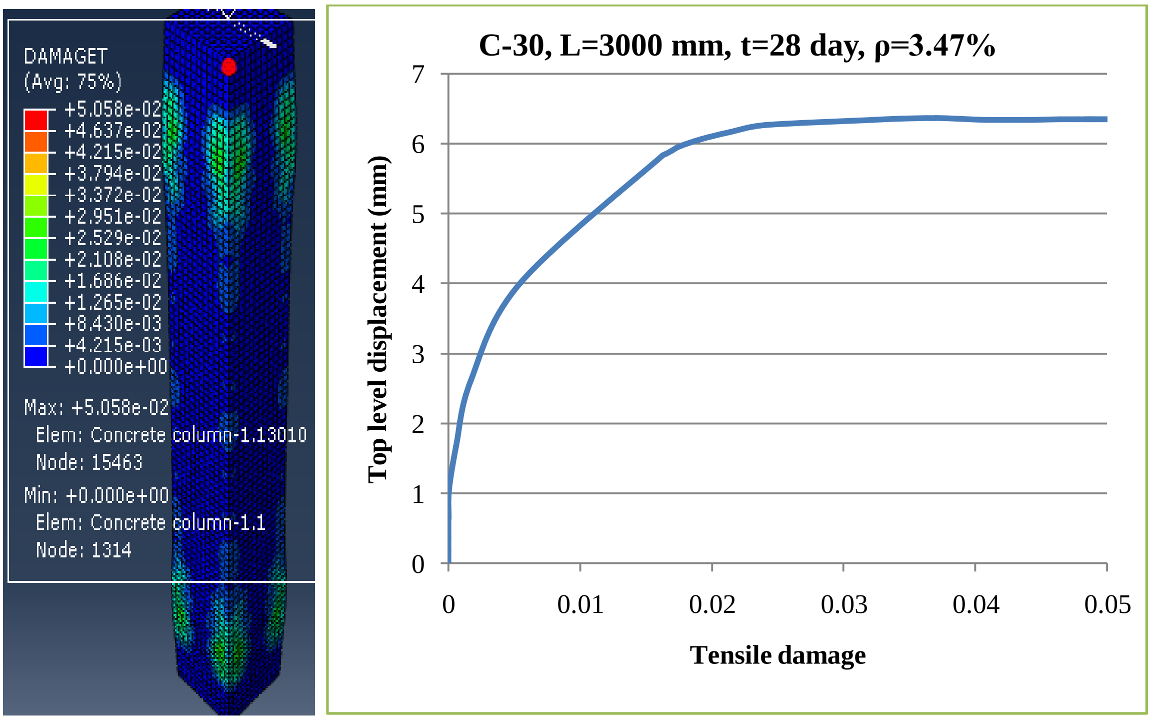


Figure C.5: Tensile damage (t=28 days)

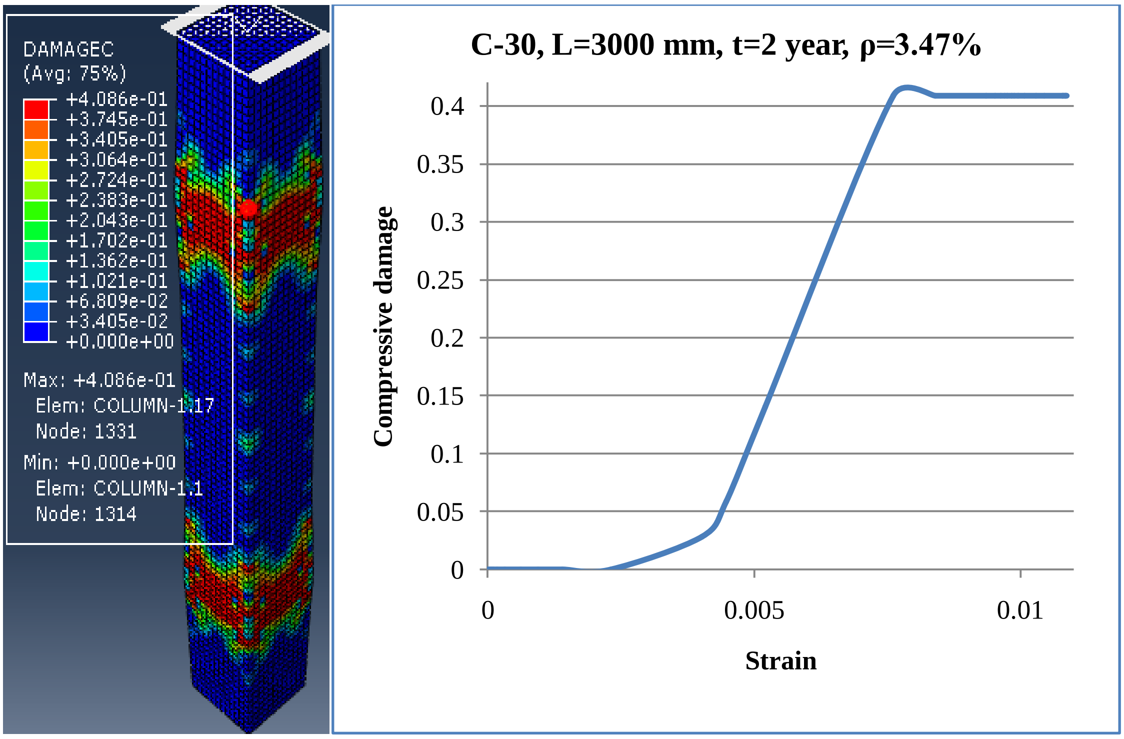


Figure C.6: Compression damage (t=2 years)

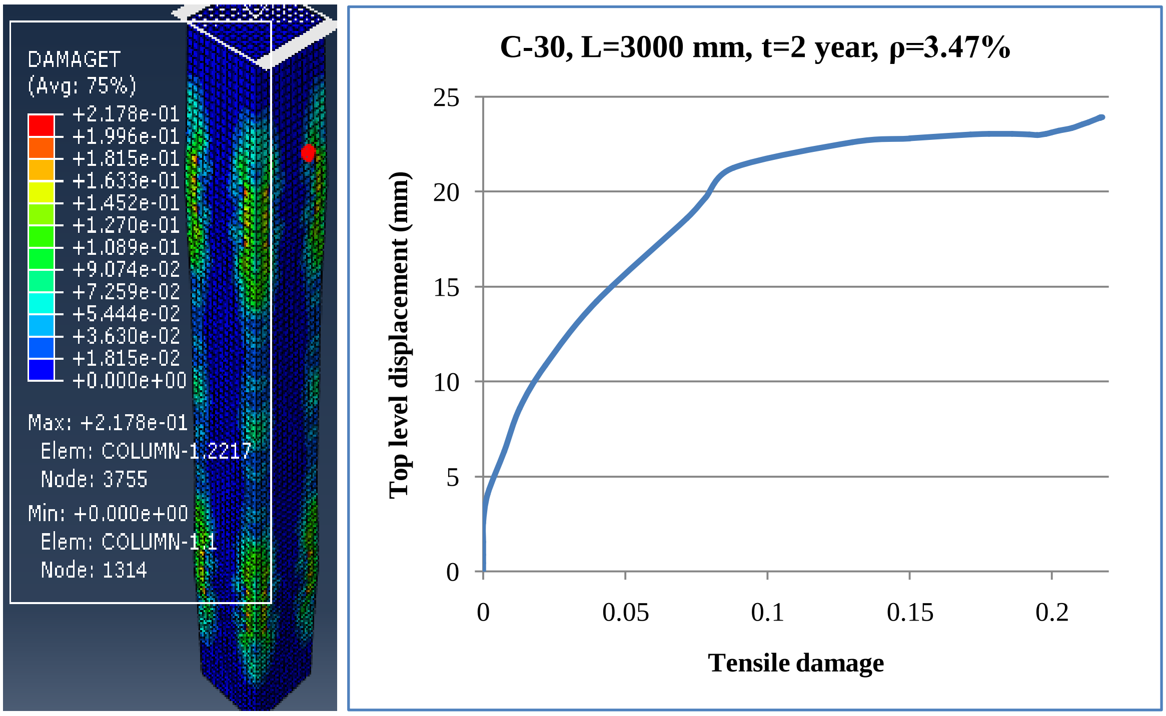


Figure C.7: Tension damage (t=2 years)

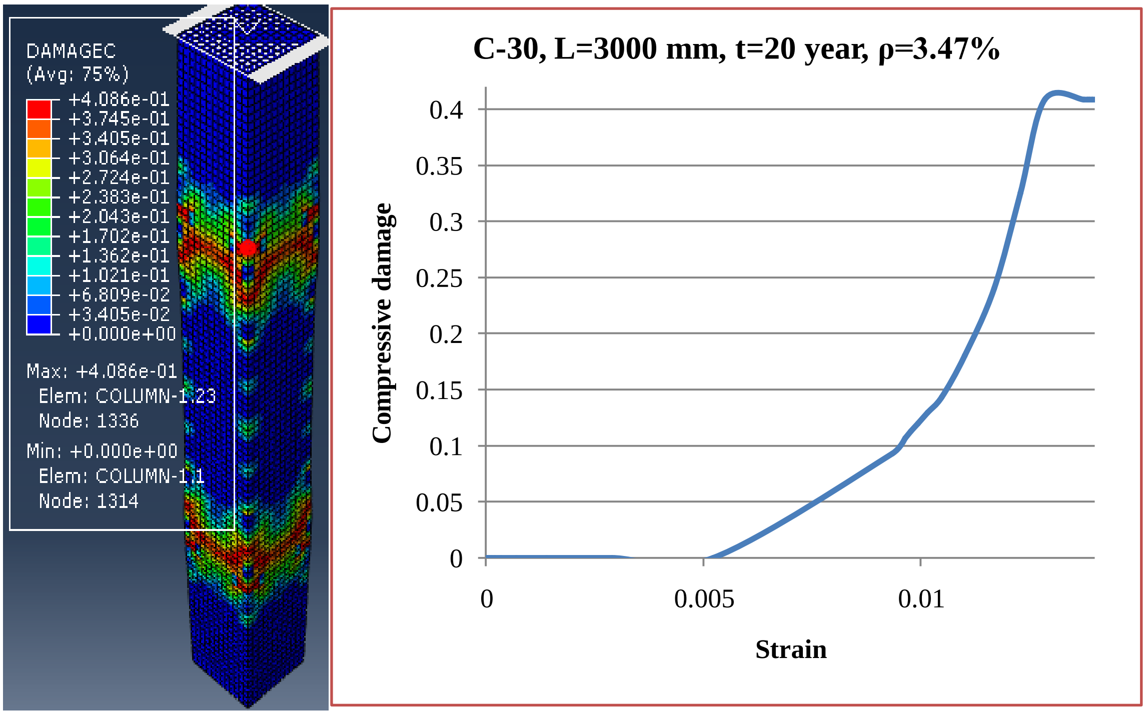


Figure C.8: Compression damage (t=20 years)

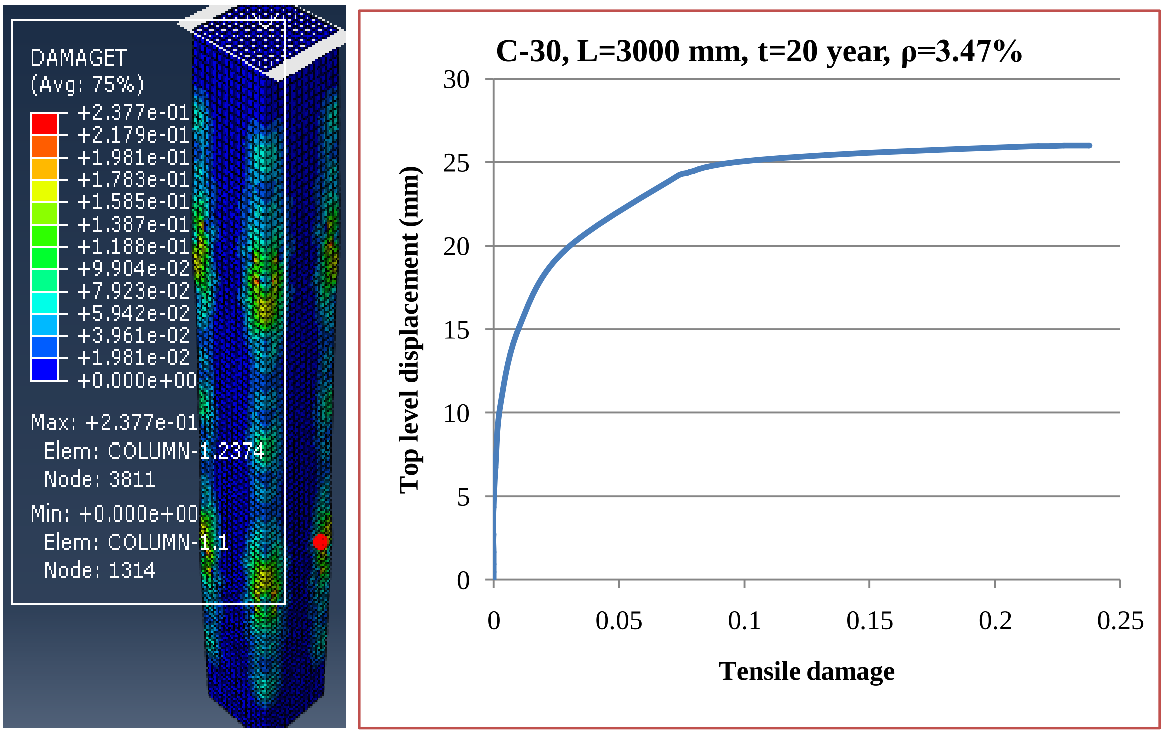
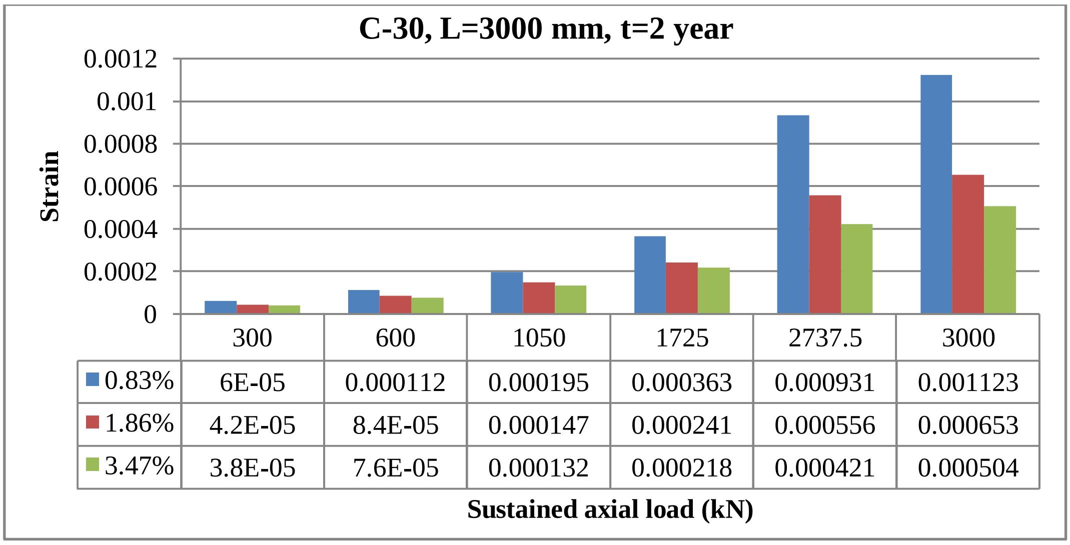
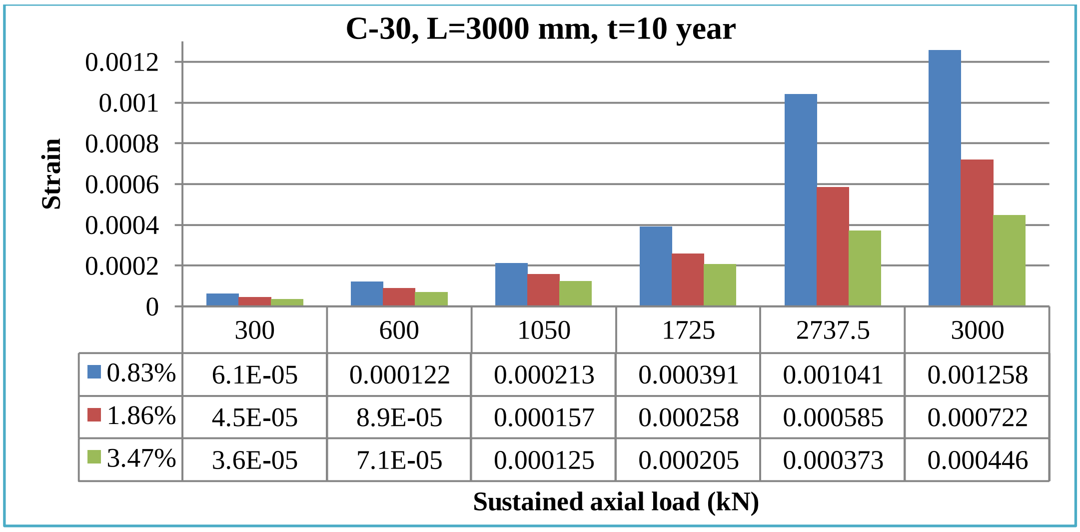


Figure C.9: Tension damage (t=20 years)



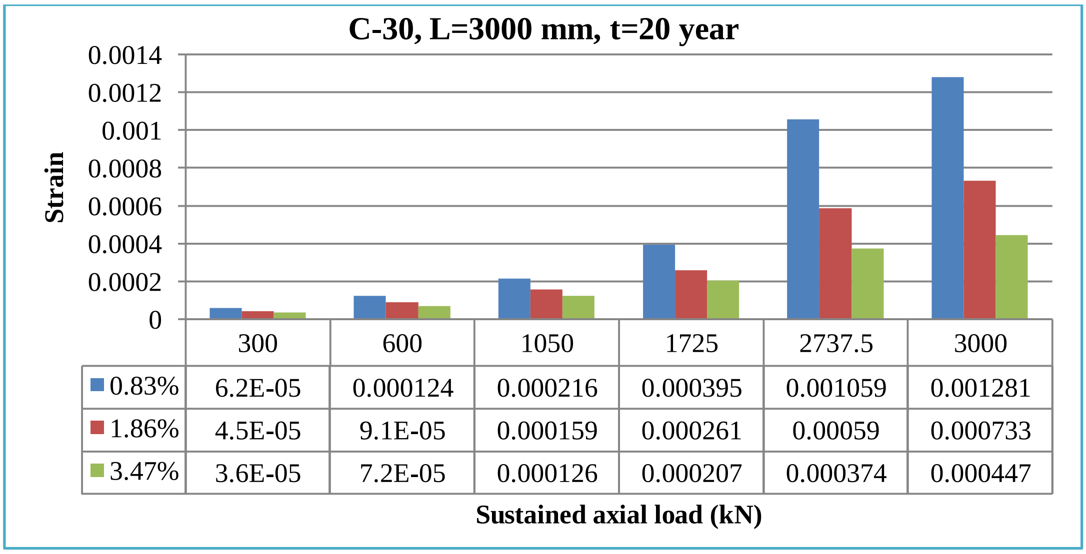
	300	600	1050	1725	2737.5	3000
0.83%	6E-05	0.000112	0.000195	0.000363	0.000931	0.001123
1.86%	4.2E-05	8.4E-05	0.000147	0.000241	0.000556	0.000653
3.47%	3.8E-05	7.6E-05	0.000132	0.000218	0.000421	0.000504

Figure C.10: Concrete strain response for different reinforcement ratio (t=2 years)



	300	600	1050	1725	2737.5	3000
0.83%	6.1E-05	0.000122	0.000213	0.000391	0.001041	0.001258
1.86%	4.5E-05	8.9E-05	0.000157	0.000258	0.000585	0.000722
3.47%	3.6E-05	7.1E-05	0.000125	0.000205	0.000373	0.000446

Figure C.11: Concrete strain response for different reinforcement ratio (t=5 years)



	300	600	1050	1725	2737.5	3000
0.83%	6.2E-05	0.000124	0.000216	0.000395	0.001059	0.001281
1.86%	4.5E-05	9.1E-05	0.000159	0.000261	0.00059	0.000733
3.47%	3.6E-05	7.2E-05	0.000126	0.000207	0.000374	0.000447

Figure C.12: Concrete strain response for different reinforcement ratio (t=20 years)

BIOGRAPHY OF THE AUTHOR

Galata Kabeba Fole was born in June 1991 in Ethiopia, Oromia Regional State Gindeberet Woreda. He attended his undergraduate studies in the Civil Engineering program at the University of Haramaya, Ethiopia starting from 2010 until 2014. He graduated from Civil Engineering program and got his Bachelor of Science in Civil Engineering in June 2014.

He has worked at Wolega University in the position of assistant lecturer starting from August 2014 until May 2016. He got the chance of following a postgraduate scholarship Master of Science degree in Civil Engineering given by Ethiopia Road Authority at Addis Ababa Science and Technology University, specializing in the field of Structural Engineering. He awarded the Master of Science in Structural Engineering from Addis Ababa Science and Technology University in February 2019.